Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia

THE CHOICE OF MULTI-EMISSION METRICS AND IMPLICATIONS ON INTERNATIONAL CLIMATE CHANGE NEGOTIATIONS: THE CASE OF BRAZIL

Maria Cecilia Pinto de Moura

Tese de Doutorado apresentada ao Programa de Pós-Graduação em Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Planejamento Energético.

Orientador: Roberto Schaeffer

Rio de Janeiro
Agosto de 2013

THE CHOICE OF MULTI-EMISSION METRICS AND IMPLICATIONS ON INTERNATIONAL CLIMATE CHANGE NEGOTIATIONS: THE CASE OF BRAZIL

Maria Cecilia Pinto de Moura

TESE SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA (COPPE) DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE DOUTOR EM CIÊNCIAS EM PLANEJAMENTO ENERGÉTICO.

Examinada por:

Prof. Roberto Schaeffer, Ph.D.

Prof. Alexandre Salem Szklo, D.Sc.

Prof. Luiz Pinguelli Rosa, D.Sc.

Prof. André Frossard Pereira de Lucena, D.Sc

Prof. Pedro Leite da Silva Dias, Ph.D.

Profª. Suzana Kahn Ribeiro, D.Sc

RIO DE JANEIRO, RJ - BRASIL

AGOSTO DE 2013

Moura, Maria Cecilia Pinto de

The choice of multi-emission metrics and implications on international climate change negotiations: the case of Brazil / Maria Cecilia Pinto de Moura – Rio de Janeiro: UFRJ/COPPE, 2013.

XXI, 205p.: il.; 29,7 cm.

Orientador: Roberto Schaeffer

Tese (doutorado) – UFRJ / COPPE / Programa de Planejamento Energético, 2013.

Referencias Bibliográficas: p. 162-168.

1. Climate change 2. Global warming and temperature potentials 3. Emission reduction I. Schaeffer, Roberto II. Universidade Federal do Rio de Janeiro, COPPE, Programa de Planejamento Energético. III. Título.

To Eric and Philip, and future generations.

AGRADECIMENTOS

Professor Roberto Schaeffer, como posso agradecer a gentileza com a qual me acolheu, desde a primeira conversa de mais de uma hora, quando nem me conhecia? E depois durante todo o processo de amadurecimento, incentivando-me e guiando-me pacientemente? Professor Alexandre Szklo, como posso agradecer por ter compartilhado generosamente o seu profundo conhecimento, que engloba as disciplinas humanísticas, enriquecendo a visão profissional? Agradeço ao Professor André Lucena, cuja trajetória brilhante de aluno a professor pude acompanhar, por ter dado início ao processo que permitiu a continuação da minha trajetória no universo da pesquisa. Dedico um agradecimento especial aos demais menbros da minha banca, Professores Luiz Pinguelli Rosa, Pedro Leite da Silva Dias e Suzana Kahn Ribeiro. Agradeço a Glen Peters, por ter-me acolhido calorosamente em Oslo.

Parte do meu amadurecimento neste processo se deu pela felicidade de fazer parte do Cenergia, onde agradeço a todos os pesquisadores e colegas que compartilharam comigo anos de um convívio sempre alegre e enriquecedor. Obrigada, Ana, Bruno, David, Esperanza, Eveline, Isabella, Joana, Larissa, Mauro, Paulo, Pedro, Rafael, Raul, Régis, Susi. Agradeço aos colegas Guilherme de Azevedo Dantas, Alberto Villela e Raymundo Aragão Neto pelas muitas conversas. Obrigada, Professores Aurel Lazar, Renato Galvão Flôres Junior, Amaro Pereira Júnior e Ricardo Rhomberg Martins. Não posso deixar de agradecer à Sandrinha, ao Paulo, à Simone, à Bia, à Queila, e ao Fernando, pelo apoio amigo durante todos estes anos.

Agradeço a minha família pelo apoio constante, pela paciência e pelos incentivos nos momentos mais difíceis ao longo dos anos de trabalho, e por estarem sempre confiantes no meu sucesso: meu marido Peter; meus filhos Eric e Philip; Isabel e Ricardo, Rodrigo, Heitor e Angela, Eleonora e Tim. Agradeço aos meus amigos Eduardo, Maria Alice, Laura, Majed e Tom, por entenderem a razão dos meus desaparecimentos por longos períodos e por estarem, no entanto, sempre presentes. E à minha mãe Déa, e ao meu pai, o falecido Embaixador Heitor Pinto de Moura, dedico o mais carinhoso agradecimento, por terem sido eles a minha principal inspiração em todo este belo processo.

Sou grata à CAPES, à FAPERJ e ao CICERO (Oslo) pelo apoio financeiro que possibilitou a execução deste trabalho.

Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

DIFERENTES MÉTRICAS DE CONTABILIZAÇÃO DE EMISSÃO DE GASES DE EFEITO ESTUFA E SUAS IMPLICAÇÕES EM NEGOCIAÇÕES INTERNACIONAIS SOBRE MUDANÇAS CLIMÁTICAS: O CASO DO BRASIL

Maria Cecilia Pinto de Moura

Agosto/2013

Orientador: Roberto Schaeffer

Programa: Planejamento Energético

O objetivo desta tese é avaliar o efeito da escolha de métrica na equivalência das emissões de gases de efeito estufa. Quantifica-se o grau de variação da percepção do impacto climático causado pelos gases, especialmente em setores intensivos em emissões de metano ou óxido nitroso. Uma comparação entre as métricas GWP e GTP é efetuada, com o intuito de quantificar os efeitos de dois fatores temporais, o horizonte de tempo e a agregação de pulsos de emissão, nas emissões equivalentes. Primeiro são analisadas as características gerais das métricas de emissão, seus desafios e vantagens, e é apresentada a formulação das métricas. Elaboram-se séries temporais de emissões provenientes da combustão fóssil a partir do balanço energético brasileiro, e são apresentadas as emissões dos setores da economia brasileira, com base no Segundo Inventário brasileiro. São calculadas a seguir as variações entre as métricas tradicionais fixas e as variantes variáveis, e identificados 4 fatores que determinam estes padrões de variação. Com base nestes fatores, é feita uma análise sistemática dos padrões de variação. Por fim determinam-se as implicações desta análise para a escolha de métricas e elabora-se um guia para tomadores de decisão, tendo em vista a importância das emissões equivalentes nas negociações internacionais climáticas. Os resultados demonstram que a escolha crítica é entre GWP e GTP, em particular para horizontes de tempo distantes. A variação entre a métrica fixa e variável é menos significativa, mas esta escolha se torna mais importante na medida em que o horizonte de tempo é mais curto, especialmente para o GTP. Quantifica-se também a variação devido à escolha de horizonte de tempo para cada métrica.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

THE CHOICE OF MULTI-EMISSION METRICS AND IMPLICATIONS ON INTERNATIONAL CLIMATE CHANGE NEGOTIATIONS:
THE CASE OF BRAZIL

Maria Cecilia Pinto de Moura

August/2013

Advisor: Roberto Schaeffer

Department: Energy Planning

The objective of this dissertation is to analyze the effect of the choice of metric on greenhouse gas emission equivalency. This aim is achieved by quantifying the degree of variation in the perception of climatic impact caused by the gases, particularly in methane- or nitrous oxide-intensive sectors. The global warming and global temperature potential (GWP and GTP, respectively) are compared, aiming at quantifying the effect of two temporal factors, time-horizon and emission pulse aggregation, on equivalent emissions. First, the general characteristics of emission metrics are analyzed and the formulations of the two metrics are presented. Emission time-series due to fossil combustion are calculated, and sector emissions for Brazil, based on the Second Inventory, are presented. The variation between the traditional fixed metrics and the variable variants are calculated and 4 factors which determine the patterns of these variations are identified. Based on these factors, an extensive and systematic analysis of the variation patterns is performed. Finally, the study looks at the implications of this analysis for the choice of metrics and guidelines for policymakers are developed, given the importance of equivalent emissions in international climate change negotiations. Results show that the choice between GWP and GTP is critical, especially for distant time-horizons. The variation between the fixed and variable metrics is less significant, but this choice become more important as the time-horizon becomes smaller, in particular for GTP. The variation due to the choice of time-horizon for any one metric is also quantified.

Contents

List of Tables

List of Tables in Appendices

List of Figures

List of Figures in Appendices

List of Equations

List of Acronyms

AGTP. Absolute Global Temperature Potential

AGWP. Absolute Global Warming Potential

BC. Black carbon

CFC. Chlorofluorocarbon

CO_2. Carbon dioxide

EBM. Energy Balance Model

ECM. Emission Center of Mass

EDGAR. Emission Database for Global Atmospheric Research

GCM. General or Global Circulation Model

GHG. Greenhouse gas

GTP. Global Temperature Potential

GWP. Global Warming Potential

IEA. International Energy Agency

IPCC. Intergovernmental Panel on Climate Change

IPPU. Industrial Processes and Product Use

LCA. Life-cycle assessment or analysis

LUC. Land-use change

MCTI. Ministério da Ciência, Tecnologia e Inovação

N_2O. Nitrous oxide

NMVOC. Non-methane Volatile Organic Compound

NO_x. Nitrogen oxide

NRI. Normalized Real Impact

PM. Particulate Matter

PNMC. Plano Nacional sobre Mudança do Clima, Política Nacional sobre Mudança do Clima

RC. Radiative-convective model

TH. Time-horizon

UD-EBM. Upwelling-Diffusion Energy Balance Model

UNFCCC. United Nations Framework Convention on Climate Change

VOC. Volatile Organic Compound

WG. IPCC Working Group

1. Introduction

Constructing and maintaining sustainable developmental pathways depends on the design of equitable climate change policies. The accurate assessment and comparison of global climate change impacts caused by greenhouse gases (GHGs) emissions over time are indispensable prerequisites in this endeavor. The development of effective mitigation strategies hinges on the evaluation of emission trade-offs between GHGs and it should be possible to compare the impacts' relative importance on a practical, reliable and common quantitative scale, agreed upon in advance by all decision makers.

In the Expert Meeting on the Science of Alternative Metrics (IPCC, 2009), the Intergovernmental Panel on Climate Change (IPCC) made a series of key recommendations to the research community. One of these addresses the relationship between policy frameworks and metrics: first, to "study implications of choice of alternative metrics for outcomes such as emissions of different gases, climate change outcomes, and costs (especially for specific countries or sectors)" and second, to "investigate the potential for extending the multi-gas strategy to short-lived pollutant emission". This study aims to make original contributions to both these objectives.

In a broad sense, a metric can be defined as a standard of measurement, or a quantitative measure of the degree to which a component of a system or an entire system possesses a given attribute. Metrics are necessary as proxies for climate change impacts, and their development depends on input parameters drawn from variables relating to a highly complex climate system. The quantification of these variables, subject to great uncertainty and continued debate in the scientific community, constitutes the first level of challenge in the development of metrics. Once variables have been quantified, the design of metrics based on these variables presents the next level of challenge. For instance, the quantification of the atmospheric lifetime of a greenhouse gas determines the precision of an emission metric, while the climate sensitivity determines the precision of a metric based on temperature change. Finally, the metric most suited for specific climate policies must be chosen. This challenge involves having clear policy goals and minimizing value judgments, focusing on the fundamental fact that chosen metrics must be practical, reliable and suitable for comparisons on a common scale[1].

The diversity of physical and chemical characteristics of greenhouse gases, their complex atmospheric interactions over time and the diversity of impacts on the planet make multi-gas quantitative comparisons a subject of much controversy. Climate change impacts manifest themselves in various ways, through physical manifestations such as changes in temperature, precipitation, wind, ice-coverage, sea-level and patterns of extreme events, as well as through biological, economic and sociological manifestations. Impacts are also subject to different irreversibility and discontinuity characteristics. The importance and intensity of impacts can be perceived differently, and adapted to based on different strategies, depending on physical factors such as location and geographical characteristics, and on degree of economic and technological development, and on cultural characteristics. The nature of the origin of impacts is also subject to complexity, such as the differentiation between anthropogenic and non-anthropogenic sources. The divergence between local origin and global effect of the impact gives rise to issues relating to historical responsibility for emissions. Temporal considerations, such as when emissions take place, how emissions evolve over time, when impacts should be assessed, and how emission constraints should evolve over time, introduce particularly difficult challenges.

The global warming potential (GWP) multi-gas equivalency metric has had a prominent role in policy negotiations since the GWP with a fixed 100-year time-horizon (GWP-100) was proposed by the IPCC as a metric to convert multi-gas emissions into carbon dioxide equivalent (CO_2-equivalent or CO_2-eq) emissions on a common scale, mainly because of its transparency and simplicity of use, and was adopted by the Kyoto protocol of the United Nations Framework Convention on Climate Change

[1] The common scale adopted here refers to a cost-effective framework, rather than a cost-benefit one. In the former, the policy is concerned with meeting environmental targets regardless of cost (but minimizing cost within possibilities), so the metric should be on an environmental common scale. In the latter, the policy objective is a joint one, concerned with minimizing mitigation cost as well as achieving environmental goals, so the metric needs to be on a monetary common scale.

(UNFCCC)[2]. The limitations of the GWP have been extensively documented (the most relevant of these studies will be reviewed in Chapter 4). More recently, the comparative advantages of the alternative global temperature potential (GTP) and other metrics have also been the subject of much debate. There have been studies comparing the metrics from various perspectives and studies comparing values of GWP and GTP for different time-horizons for a variety of substances (Shine et al., 2007; Peters et al., 2011). The IPCC recommends that research focus on the new role of GTP as a possibly more reliable metric for use in policy contexts, compared to GWP (IPCC, 2009).

There have been many studies addressing the main limitation of GWP which concerns us here, namely the treatment of temporal issues. These studies include the treatment of time in life-cycle analysis (Levasseur et al., 2010; Peters et al., 2011) and the study of short-lived GHGs from the transport sector (Fuglestvedt et al., 2010; Peters et al., 2011). The sensitivity of short-lived GHGs to the treatment of time is a particularly strong justification to study the effect of the time-horizon on metrics. CO_2 is a non-reactive GHG, as reflected in its long atmospheric residence time, so its contribution to radiative forcing must be considered for many decades, while capturing the effect of short-lived emissions requires a much shorter time-horizon, on the order of 5 years for pollutants such as black carbon, nitrogen oxides and volatile organic compounds (BC, NO_x, VOC). Wallington et al. (2011) state that for a time-horizon of 1 year, aviation emissions cause 6.5 times the warming caused by road transport, while for 10 years the difference is less than 3 times.

Although there has been much discussion in the literature about the treatment of time in metrics, there have not been many studies comparing the traditional ‘fixed’ GWP and GTP, with the dynamic or ‘variable’ GWP and GTP. The fixed GWP or GTP are based on a fixed time-horizon, regardless of the moment when the emission pulses occur. The variable GWP or GTP weigh emission pulses according to their distance from the moment of impact (these different forms of the metrics will be described in detail in Chapter 4). Berntsen and Fuglestvedt (2008) calculate transport sector temperature impact at different time-horizons, but only due to emissions in the year 2000, rather

[2] In Article 5.3, the Kyoto Protocol states that “the global warming potentials used to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases listed in Annex A shall be those accepted by the Intergovernmental Panel on Climate Change […]" (IPCC, 1998).

than for varying emissions over a period, as is done in this study. An analysis of temporal issues in a variety of specific emission scenarios allows the limitations of the GWP-100 metric as a methodology for comparing the impact of GHGs to acquire practical significance in policy contexts, and brings the importance of metric choice to the forefront of climate policy.

Furthermore, some studies focus on theoretical analyses which are independent of emission scenarios, while others address the impact of temporal issues when metrics are applied to real multi-gas emission scenarios. These scenarios, however, are generally quite specific, as in analyses of specific sectors, such as the transport sector, or as in LCAs of biofuels. To date no detailed comparative studies encompassing all sectors of an economy and the treatment of temporal issues in metric choices have been found in the literature.

The main objective of this study is to quantify the variability resulting from the choice of multi-gas equivalency metric, from a temporal perspective, and to show how this choice can be critical in evaluating the impact of greenhouse gases. This study illustrates how the design and implementation of time-sensitive policies is only possible if policymakers are well-informed about the options available in the selection of metrics and their limitations. The major original contribution in this study is an investigation of the degree to which simple temporal aspects of GWP and GTP affect the relative perception of the climate change 'harm' caused by the three main GHGs, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), in the context of Brazilian GHG emissions scenarios relative to the 1970-2010 period.

The Brazilian Ministry of Science, Technology and Innovation (MCTI, previously MCT), in its Second Communication to the UNFCCC (MCT, 2010), states that Brazil's official position favors the use of GTP, citing GWP's main limitations, and compares the CO_2-equivalent contributions of CH_4 in 2005 based on GWP-100 and GTP-100. Based on GWP-100, CH_4 emissions are 380.2 Mt (17.3%), out of Brazil's total of 2,192.6 Mt, while based on GTP-100, CH_4 emissions are 90.5 Mt (4,8%) out of 1,879.0 Mt[3] (MCT, 2010; see Appendix A). This study takes the MCT's analysis further, by

[3] The emission values for the 10 GHGs considered by the MCT are listed in Appendix A.

including the entire period reported in the Second Inventory[4] (1990-2005), and by taking into account 4 time-horizons and time-dependent metrics, in a total of 16 metrics.

Aside from the 3 main GHGs, the other greenhouse gases for which the Second Inventory lists emissions data, namely the 4 HFCs (125, 134a, 1431, 152a), CH_4, C2F6 and SF_6, were not considered in this study. The contribution of these gases is small compared to the contributions of CO_2, CH_4 and N_2O (based on GWP-100 and GTP-100 values used in this study, shown in Chapter 4), in 2005 the three main GHGs contributed 99.4% and 99.7% of total Brazilian emissions of all 10 GHGs (MCT, 2010; see Appendix A), while the above-mentioned 7 GHGs make up the remainder), yet some of these gases are high impact, even if contributions are very small, and should not be ignored. Short-lived components such as BC, NO_x and VOC were also not considered, in spite of their current importance in the literature. These exclusions are justified here for two reasons. First, emissions data for these GHGs and pollutants in Brazil is either incomplete for the period and sectors studied, or not reliable. For instance, Levin et al. (2010) claim that synthetic fluorinates gases such as SF_6 are generally greatly underestimated. Second, their inclusion would have added a level of complexity which is beyond the scope of this study.

There has been a global focus on curbing the emission of CO_2, the major GHG. Although no climate impact assessment is easy, comparing impacts due to the emissions of one such major pollutant presents fewer challenges than comparing impacts due to multi-gas emissions. For comparisons where CO_2 is the main emitted GHG, such as for the combustion of fossil fuels, assigning responsibility for impacts is not as much of a challenge as for sectors with multi-gas emissions. Comparisons that encompass many sectors, and so must deal with the joint emissions of short-lived and long-lived substances, are especially subject to controversy. Comparisons of sectors where mainly CH_4 is emitted, such as the fugitive emissions from the energy sector, or agriculture and the waste sectors, are also especially sensitive to the choice of metric, as GWP and GTP values differ significantly for CH_4, as will be seen in this study. Multi-gas equivalency is particularly sensitive to non- CO_2 GHGs with high GWP and GTP values, such as CH_4 and N_2O. The importance of being able to accurately assess the impact of such gases relative to CO_2 is acknowledged, but there have been few studies which quantify

[4] The Second Inventory was published as part of the MCT Second Communication. See a more complete discussion in Section 2.1.

the variability of multi-gas comparisons caused by the choice of metrics. CH_4, in particular, deserves to receive more attention, as many countries have started exploring their natural gas reserves more intensely. According the World Energy Outlook special report "Are We Entering a Golden Age of Gas?" (OECD/IEA, 2011), the share of natural gas in the global primary energy mix overtakes coal by 2030. By 2035, China's gas demand will surpass the European Union's total demand, India's demand quadruples relative to today, and Middle Eastern demand doubles, while recoverable resources are sufficient to sustain current production for 250 years (IEA, 2011).

In the meantime, the special report mentioned above, "Are We Entering a Golden Age of Gas?", states that unconventional natural gas resources are now estimated to be as large as conventional resources, while also stating that revised estimates for shale gas production emission factors are much higher than previous estimates and many times higher than for conventional gas (OECD/IEA, 2011) According to a pilot study by the National Oceanic and Atmospheric Administration (NOAA), results suggest that venting emissions from oil and gas production in northeastern Colorado has been grossly underestimated, with uncertainties as high as twice the emission values reported in current inventory estimates (Pétron et al., 2012). CH_4 emissions from enteric fermentation, landfills, coal mining, manure management and the oil and gas industry could neutralize efforts made to reduce to use of coal.

A Brazil study-case is quite pertinent, considering that in 2005 Brazil's CH_4 emissions amounted to approximately 18 Mt and increased by 37% between 1990 and 2005 (MCT, 2010). The country has the second largest bovine[5] herd in the world, after India, and 63.4% of its total CH_4 emissions in 2005 were accounted for by enteric fermentation[6]. Brazil has the world's tenth largest technically recoverable shale gas reserves, but the market is still small when compared to those of the OECD and the U.S (Lage et al., nd). There is much controversy concerning the CH_4 emissions of hydroelectric power plants (Rosa et al., 2004, 2006).

[5] 212.8 million in 2011 (IBGE, 2013a)

[6] The remaining was due to burning biomass in the land-use change and forestry sector (16.8%), waste management (9.6%), animal waste, rice cultivation and burning biomass in the agricultural sector (7.1%), and the energy and industrial sectors (3%) (MCT, 2010).

The country's N_2O emissions, which is long-lived but has a high impact potential, are also not negligible, particularly in the agriculture and livestock sector, which accounted for 87.2% of the country's total 546 Kt emitted in 2005[7].

In this study, two main emission scenarios are used to calculate GWP and GTP-based impacts in 2020, 2035, 2050 and 2100. For each of the emission scenarios, CO_2-equivalent emissions are calculated for the multi-gas mix using fixed and variable GWP and GTP metrics (fixed GWP, fixed GTP, variable GWP and variable GTP). A thorough comparative analysis is conducted and the variability between the choices is mapped.

The emissions data used in this study is derived from two sources, the Brazilian Energy Balance (BEB) (EPE, 2011) and the MCT (MCT, 2010).

Scenario 1 refers to the emissions from the energy sector in the 1970-2010 period, as calculated from BEB energy data. This scenario is analyzed for two cases: fossil fuel and biomass combustion (Scenario 1A); and fugitive emissions, based on MCT emissions data (Scenario 1B[8]). In Scenario 1A, emissions for all-sector emissions for the single year 2010 and for the isolated charcoal sector are presented as well.

Scenario 2 refers to all sectors of Brazil's economy, that is, Brazil's total emissions, in the 1990-2005 period. Unlike Scenario 1, the emissions data for this scenario was not calculated in this study. In this scenario the data used is that published in the MCT Second Inventory (referred to in this study as MCT II - see MCT, 2010).

One parallel original contribution here was the development of a CO_2, CH_4 and N_2O emissions time-series database for fossil fuel and biomass combustion in the Brazilian economy in the 1970-2010 period, used in the Scenario 1 analysis. Calculated from the annual BEB statistics, this database details emissions for 25 final consumption sectors due to each sector's combustion of 9 primary and 15 secondary fuels.

---

[7] The remainder was emitted by the industrial sector (4.2%), land-use change (3.8%), waste management (2.6%) and energy sector (2.2%) (MCT, 2010).

[8] The nomenclature for the scenarios is based on IPCC activity and source structures. For IPCC sector 1 (Energy), the individual category 1A accounts for 'Fuel Combustion Activities', and is equivalent to scenario 1A here; the individual category 1B accounts for 'Fugitive emissions from fuels', and is equivalent to scenario 1B here. Individual category 1C accounts for 'Carbon dioxide Transport and Storage' and is not considered in this study. There is no equivalence in nomenclature between scenario 2 and 3 as defined here and IPCC categories.

These fuel emission time-series were compared with those listed for Brazil in existing global databases, which also use energy balances, and with the emissions reported in Brazil's MCT II (MCT, 2010). This comparison brings out some relevant qualitative issues concerning the consequence of assumptions made in reporting choices, particularly in the steel sector and the charcoal-production sector, as well as in the choice of emission factors.

Another parallel original contribution is the quantification of the degree to which the impact of applying a fixed metric may to lead to underestimation or overestimation of impacts at a fixed time-horizon, based on the 'shape' of the emission series and its period relative to the year 2000. An index, the normalized real impact, is developed as a discount factor to be applied to fixed GWP and GTP metrics before these fixed metrics can be compared to the variable metrics. Based on this index, we show that the MCT II emission series, used for total Brazil emissions, is adequate for comparison, but that emissions based on the BEB series leads to a significant underestimation for fixed GTP-based CH_4 impacts in 2050.

This study is organized as follows. After the Introduction, Chapter 2 discusses the global relevance of Brazil in the climate change context and addresses the consequences of the country's changing energy emissions scenario, as well as of the changing land-use emissions scenario. Chapter 3 discusses the challenges of choosing metrics in a policy context. Chapter 4 addresses the methodology used in the study, with an initial short discussion about climate models and the climate change cause and effect chain, followed by a detailed presentation of emission metrics. Here, we first look at the general formulation of an emission metric and systematically develop the mathematical formulations of the GWP and GTP used in this study. Still in this chapter, we address the characteristics and limitations of these metrics, and present the formulations of CO_2-equivalency which take into account temporal considerations. The energy and emissions data, the quantitative results and the analysis of the results are presented in Chapters 5, 6 and 7, respectively. Finally, Chapter 8 discusses the implications of the results for climate change negotiations and the last chapter, Chapter 9, presents suggestions for further studies.

It should be noted that there is no separate bibliographical review chapter. The choice was made to insert literature reviews throughout the entire study, as the literature reviewed covers a broad range of subjects. Nevertheless, the bulk of the bibliographical review is presented in Chapter 4.

2. Global relevance of Brazil in the climate change context

A case-study of Brazilian multi-gas emissions, from the perspective of different metrics, is globally relevant for two main reasons. First, Brazil has had a historical global role and is a major player in climate-change negotiations. Second, the composition of the Brazilian GHG emissions mix is changing. Although deforestation rates have been decreasing, the electricity matrix is changing, as hydroelectric potential is depleted and fossil-fuel energy consumption increases. The first part of this chapter presents an overview on Brazil's role in international climate change negotiations and an overview of its domestic climate change agenda. The second part looks at the reasons behind the changes in the Brazilian GHG emission mix.

2.1. Brazil's role in climate change policy

Brazil's has made significant direct and indirect contributions to the effort of reducing global emissions, from active participation in the United Nations Framework Convention on Climate Change (UNFCCC) policy negotiations, through implementation of national policies for the mitigation of global warming. Insofar as policy instruments are concerned, Brazil's first international contribution was the 1994 ratification by the Brazilian Congress of the UNFCCC, which resulted from the United Nations Conference on Environment and Development (Rio-92). According to the principle of "common but differentiated responsibilities" (UNFCCC, 2013) of developed and developing countries (respectively Annex I and non-Annex I countries), Brazil did not assume any commitments to reduce emissions, but nonetheless participated actively in the negotiations.

At the time of the Kyoto Protocol negotiations, at the Third Conference of the Parts, in response to the Berlin Mandate (UNFCCC, 1997), the delegation from Brazil contributed to the discussion of how to determine objective criteria for sharing mitigation burden and the definition of emission reduction targets. The Brazilian Proposal (UNFCCC, 1997a) was not adopted in the Kyoto Protocol, but became the subject of continued debate (den Elzen and Schaeffer, 2002; Höhne, 2002; UNFCCC, 2002b; Rosa et al., 2004). The Proposal recognizes that for policy purposes, in spite of the complexity of climate impact manifestations, a single variable should be developed to act as proxy for these impacts. A central concern, according to the Proposal, would be the assumption of a relationship between a country's emissions and the resultant climate impact, with a focus on Annex I countries. As a measure of this impact, the increase in average global temperature was proposed due to emissions of CO_2, CH_4 and N_2O, with a temperature increase ceiling defined for each country. A ceiling increase for several sub-periods between 1990 and 2020 was calculated based on specifically defined effective emissions starting in 1990. The temperature increase ceiling was proposed as a fairer measure for the definition of emission reduction targets than annual emissions. Any country exceeding its ceiling would be given the opportunity to purchase "temperature increase credits" from other countries which did not exceed their ceiling. Advantages of this "polluter-pays-principle" is the fairness in the attribution of relative responsibility, proportional to cumulative emissions and corresponding induced temperature increase, and the notion of a comprehensive budget which can include all GHGs for each country, providing flexibility in the choice of policies.

More recently, during COP-16[9], Brazil has given continuity to the underlying idea of the Brazilian Proposal by officially recognizing the limitations of the use of GWP. In Brazil's Second Inventory, emissions are reported in unit mass rather than in CO_2-equivalent, so as to avoid the use of the GWP-100 metric. Furthermore, for the sake of illustration, the country's 2005 multi-gas emissions in GWP and GTP-based metrics are compared: Brazil emitted 18,107 Gg of CH_4 in 2005[10], which corresponds to 380,241 Gg CO2-eq after conversion using a GWP of 21, yet corresponds to 90,534 Gg after conversion using a GTP of 5 (see Appendix A).

Brazil's national agenda in climate change policy has been evolving since 1999, when the Inter-ministerial Commission on Climate Change (*Comitê Interministerial sobre Mudança do Clima)* was created, leading to the institution in 2008 of the National Climate Change Plan (*Plano Nacional sobre Mudança do Clima or* PNMC)[11]. This climate change program was part of a broader science and technology development action plan, the first *Plano de Ação*, covering the period 2007-2010, also known as

---

[9] 16th session of the Conference of the Parties to the UNFCCC, which took place in Cancun, Mexico, in November 2010.

[10] In this study the full stop or period is used as the decimal mark and the comma is used as the separator for groups of thousands, corresponding to the standard in the United States.

[11] Decree nº 6263, November 21, 2007.

PACTI 1 (MCTI, 2007)[12], and included a vast array of national policies to reduce emissions, ranging from deforestation reduction, increase in the use of renewable energy, increase in industrial efficiency, waste management and others (MMA, 2008).

As a member of the Convention, Brazil took on the commitment of producing and periodically updating a National Inventory according to the Guidelines set forth by the Convention (UNFCCC, 2002). The first comprehensive emissions inventory for Brazil was published as part of Brazil's First National Communication to the UNFCCC (MCT, 2004), for the 1990-1994 period. A Second Inventory was published as part of the Second National Communication to the UNFCCC (MCT, 2010), for the 1990-2005 period[13].

In 2009, as announced by the Brazilian President at COP-15[14], a National Policy on Climate Change was introduced by means of a law[15] which establishes voluntary mitigation actions. This policy, based on the National Climate Change Plan (PNMC) described above, stipulated that Brazil's emission projections up to 2020 was to be based on the Second Inventory, makes a pledge to reduce these emissions by 36.1% to 38.9% by 2020 and specifies possible actions to achieve these results.

At the COP-17[16], Brazil declared its intention of adopting mandatory emission reduction targets, if China and India also adopted mandatory targets, and supported the implementation of the Kyoto Protocol's second commitment period, from January 2013 through December 2020.

Brazil has had an active role in the implementation of Clean Development Mechanism projects, an instrument created by the Convention with the objective of mitigating GHG emissions in developing countries. Until August 2012, Brazil had participated in 207

---

12 A second action plan covers de 2011-2014 period (PACTI 2).

13 The Second Inventory has recently been updated, with the revision of the 1990-2005 data and the inclusion of the years 2006-2010, but as this study was being undertaken, only partial data was available for the last five years. Wherever possible, the new data has been taken into account.

14 15th session of the Conference of the Parties to the UNFCCC, which took place in Copenhagen, Denmark, in December 2009.

15 Law number 12,187 - December 29, 2009.

16 17th session of the Conference of the Parties to the UNFCCC, which took place in Durban, South Africa, in December 2011.

projects, third after China, with 2,244 projects, and India, with 875 projects. Recent estimates suggest that these projects mitigated approximately 75 Mt of CO_2 equivalent[17] between 2005 and 2011 (UNEP, 2012).

2.2. Brazil's changing emissions mix

Brazil GHG emission profile differs substantially from that of developed countries not only because of the large contribution of renewable energy in its energy matrix, but also because of its high level of land-use change and deforestation.

According to the Carbon Dioxide Information Analysis Center (CDIAC, 2013), in 2009 Brazil ranked 17th in absolute CO_2 emissions from fossil fuel combustion, at 367 Mt, and ranked 128th in per capita CO_2 emissions, at 1.9 Mt[18]. According to recent studies, when other GHGs are included, using GWP-100 as a metric, Brazil's per capita emissions in CO_2-equivalent decreased from 16 Mt in 2010 to 8 Mt in 2011, and is now closer to the world average of 7 Mt CO_2-equivalent[19].

In 2009, the share of fossil fuel energy in the world energy matrix was 81% (WEO, 2011, p. 205), while in the Brazilian energy matrix that share was 51.5% (BEN, 2011; MCT, 2010)[20]. In 2010, 19.3% of the world's electricity consumption was based on renewable sources (15.9% hydro and 3.4% other renewable sources), while in Brazil that share was 50% (29% hydroelectric and 21% other renewable sources).

As a consequence of this clean matrix, the relative contribution of the energy sector towards CO_2 emissions is much smaller than in developed countries. When compared to the much larger emissions from land-use change (LUC) and forestry, Brazilian emissions due to energy consumption may appear to be of secondary importance. In the 1990-2005 period, according to the MCT Second Inventory, fuel combustion emission contribution, both fossil-based and biomass-based, plus fugitive emissions, oscillated between 10.5% and 21.6% of Brazil's total CO_2 emissions. In stark contrast, land-use

[17] Calculated with a GPW-100 metric value of 21 for CH_4

[18] World average is 4.8 Mt. CDIAC absolute and per capita CO_2 emissions include cement production.

[19] These results are updates based on the MCT Second Inventory methodology and are as of yet unpublished.

[20] Brazil 2009 total primary energy production: 241 ktoe; oil, gas and coal production:124.26 ktoe. Oil contribution was 37.9%, natural gas 8.8% and coal and coal by-products 4.8%. It should be noted that the high percentage of renewables in the Brazilian energy matrix is partially due to the low inefficiency of the sugar-cane chain, particularly regarding the combustion of bagasse.

change and forestry CO_2 emission contribution oscillated between 72.8% (in 1991) and 87.0% (in 1995), with an average of about 79%, over the period, of Brazil's total CO_2 emissions for all economic sectors (MCT, 2010)[21].

Relative to the world average, the contribution of renewable energy in Brazil's energy sector is high, accounting for the sector's small contribution relative to the high-emission land-use and forestry sector. Expectations were that this 'clean' energy scenario would be maintained, and that land-use emissions would continue to be dominant, so that it made sense for mitigation efforts to focus predominantly on the higher-emission land-use and forestry sector.

Yet in spite of the smaller contribution of Brazil's energy consumption emission relative to the world, the energy sector deserves to be given greater attention, without detracting from the continued need for a global focus on deforestation. There are two reasons for this. First, deforestation rates have been decreasing. Second, the energy sector profile has been changing. Together, these two new trends define a new emissions scenario for Brazil and accentuate the importance of the energy sector in mitigation efforts.

According to Brazil's Second Inventory, CO_2 emissions due to land-use change more than doubled in 15 years, from 766.5 Mt in 1990 to 1,729.5 Mt in 2004[22]. But then, in just one year, from 2004 to 2005, there was a 27% decrease in CO_2 emissions, to 1,258.6 Mt (MCT, 2010). According to the MCT update of the Second Inventory, which at the time of this study was not yet official, land-use emissions in CO_2-equivalent for CO_2, CH_4 and N_2O, continued to decrease steadily from 2004 through 2007, with a slight increase in 2008, and have continued to decrease through 2011.

But even if Brazil's annual deforestation rate is in fact decreasing, energy related emissions are rapidly increasing. During the same period, between 2004 and 2010, fossil-fuel consumption increased 19%, from 103.3 to 127.4 Mtoe[23] (EPE, 2011). According to the MCT update of the Second Inventory already mentioned, the energy

[21] The remaining portion, after energy use and land-use, is accounted for by non-energy industrial processes, agriculture and livestock, and waste management, which together oscillated between 2.5% and 5.6% of the total in that same period.

[22] Brazil's emissions are discussed in detail in Section 5.2.

[23] toe = ton of oil equivalent, a unit of energy approximately equal to energy that can be extracted from a ton of crude oil. Defined by IEA to be 41.868 GJ (IEA, 2012a)

sector's contribution has increased from 14% of the total emissions in 2005 to 28% in 2011, while the land-use sector's contribution has decreased from 65% in 2005 to 36% in 2011.

Clearly the energy sector's contribution must become larger as a result of the land-use and forestry sector's smaller contribution. But the major driver for this increased contribution of the energy sector to emissions is the increased contribution of fossil-fuels in the production of electricity, as the country's hydroelectric potential is depleted and fossil-fuel fired thermoelectric power plants are activated in compensation.

Brazil ranks third in world hydropower potential, after China and Russia. Yet of the total 260 GW of available potential, only approximately 30% is used (Eletrobrás, 2013). Regional use is quite variable. As an example, the Paraná basin use is approximately 50%, while the Amazon basin use is slightly over 1%. The 2030 National Energy Plan (EPE, 2007) assumes that until 2030 full use would be made of the total economically viable remaining potential, which amounts to 126 GW and would include the remaining 77 GW in the Amazon basin, equivalent to the total hydroelectric installed capacity in Brazil in 2005. Studies of the environmental viability of this remaining potential are still underway, but it is expected that its use would lead to significant environmental impacts (de Araujo et al., 2010).

The run-of-river hydroelectric plants minimize this impact, as is the case of Jirau, Santo Antônio and Belo Monte, but the small reservoirs reduce the safety margins of the hydroelectric system based on large reservoirs, making it harder to regulate the interconnected grid and increasing the probability of activating thermoelectric power plants (de Lucena et al., 2010).

An insufficient transmission infrastructure is another factor which increases this probability. Approximately 18,000 km of transmission lines are planned to be operational until 2015, but 14,000 km have been subject to construction delays (ANEEL, 2013). Brazil's National Interconnected System (*Sistema Interligado Nacional*, or SIN) allows for the sophisticated management of a highly complex interconnected grid of continental dimension, but transmission infrastructure deficiencies increase the risk of the system not being able to take advantage of regional hydrological diversity.

According to recent studies by the *Empresa de Pesquisa Energética* (EPE, 2012), in 2012 SIN's average load was 60.6 GW, including losses. Load forecast for 2022 is estimated at an average 91 GW, a 50% increase relative to 2012. As a result of this, even if the plants currently under construction are accounted for, in order to generate the necessary additional 30 GW from hydroelectric power, about one quarter of the economically viable potential would have to be used, leading to probable severe local environmental impacts.

Since the hydroelectric potential cannot be taken advantage of without local environmental impacts, ongoing efforts are underway to increase the commercial scale of biomass thermoelectric power plants and to insert wind energy into the grid. Yet in the short term, the only viable large-scale solution to compliment the hydroelectric system consists of natural gas and coal-based thermoelectric power plants.

Emissions from the energy sector are thus likely to continue to increase, as new electricity demand must be met with fossil sources. Together with the slowing down of deforestation, the emissions contribution of the energy sector are becoming increasingly more important, and justifies a new focus on this sector.

This chapter focused on the relevance of Brazil as a global player in the energy arena, and on how Brazilian emissions are undergoing an important transition. In the next chapter (Chapter 3), the subject of metrics is introduced. Their characteristics and challenges are discussed from a qualitative point of view. In the following chapter (Chapter 4), the subject of metrics is presented from a mathematical perspective.

3. The choice of metrics in a policy context

Climate system parameters, such as the physical, biological or socio-economic indicators drawn from the climate change chain, can all be considered measures of degree of climate change impact, and are used in the scientific community by specialists who understand the scope of their usefulness. Scientists focus on challenges such as the quantification of the climate change parameters which are necessary as input parameters for a metric, and on the design of the structure of metrics, concerns addressed by IPCC Working Group I (as will be described in Section 4.2). The challenges facing the scientific community, however, are different from those facing decision-makers. In the design of climate policy, metrics are used by non-specialists and their use and interpretation involve subjective value judgments. There have been many studies which discuss the choice of metrics for policymaking. Fuglestvedt et al. (2003) summarize emission metrics and compare radiative forcing metric with GWP, concluding that the latter is robust for many forcing agents and that GWP's political feasibility compensates for its shortcomings. Tanaka et al. (2010) presents an overview of emission metrics and their policy applications. Fuglestvedt et al. (2010) discuss the dependence on policy contexts and the treatment of time, among other factors.

The following sections discuss some of the general challenges to be faced by policymakers in the selection of climate policy metrics (in later sections 4.4.6, 4.4.7 and 4.4.8 specific challenges concerning the choice of GWP and GTP will be addressed). Temporal issues will be discussed in detail in Chapter 4, and are not addressed separately here. At the end of this chapter, Table 1 summarizes the challenges and recommendations are made.

3.1. Responsibility

One of the main concerns in the design of climate policy is the question of responsibility for climate impacts. This concern manifests itself at two different levels. First, at the highest level, the relative contribution of anthropogenic versus natural causes must be addressed. Once this differentiation has been achieved, the question of responsibility narrows down to the anthropogenic level of local responsibility, where there is a divergence between the local origin of the forcing agents and the global nature of climate change.

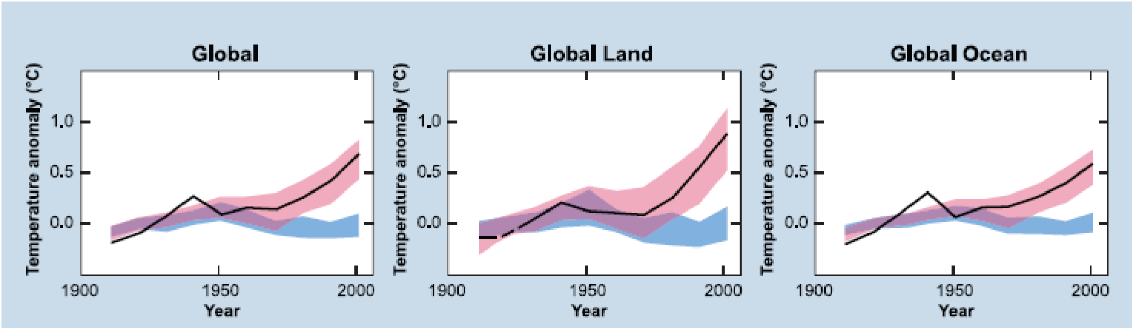
3.1.1. Divergence between anthropogenic and natural forcings

The accuracy of multi-gas equivalency metrics, particularly those derived from end-points further along the chain, depends on decoupling anthropogenic from natural contributions to climate change. A greater degree of confidence in specifying radiative forcing contributions due to various anthropogenic and natural agents and mechanisms has also increased the reliability of metrics based on radiative forcing.

In the last two decades there has been much progress in this domain, particularly since the publication of the IPCC Third Assessment Report (IPCC TAR) (IPCC, 2001), mainly because of longer observational records, better instrumentation, a larger number of improved models which when taken as an ensemble improve the representation of model uncertainty, and more research in key areas such as ocean heat content and the cryosphere (IPCC, 2007).

Temperature change from approximately 1900 to 2000 was modeled separately for natural forcings and for both natural and anthropogenic forcings, using 14 climate models. Results for land and ocean surface temperatures clearly show a statistically significant divergence between the temperature change evolution when only natural forcings are considered compared to the case when both forcings are considered. A comparison of temperature changes reported by the IPCC Fourth Assessment Report (IPCC AR4) is summarized in Figure 1.

.



Notes:
Black line: decadal averages of observations for 1906-2005 plotted against centre of the decade and relative to corresponding average for 1901-1950.
Blue shaded band: 5% to 95% range for 19 simulations from 5 climate models using only natural forcings from solar activity and volcanoes.
Red shaded band: 5% to 95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

Figure 1 - Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings.

Source: IPCC AR4, from Figure FAQ 9.2.

Net anthropogenic radiative forcing since pre-industrial times, at the time of IPCC Fourth Assessment Report, was considered to be 1.6 Wm^{-2}, with the 90% confidence interval ranging from 0.6 to 2.4 Wm^{-2}, while net natural radiative forcing, due to solar irradiance, contributed to just 0.12 $Wm-^{2}$ (see Figure 2).

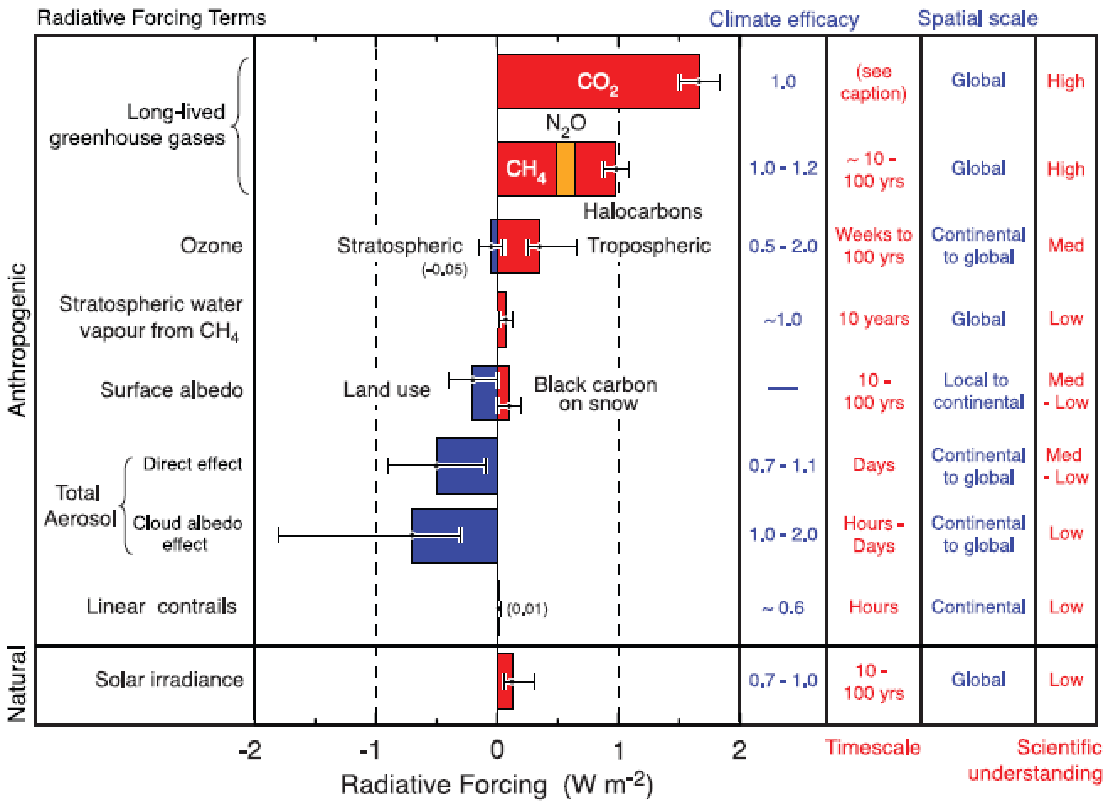


Figure 2- Global mean radiative forcing from various agents and mechanisms between 1750 and 2005.

Source: IPCC, 2007, WG1, Chapter 2, Figure 2.20.

Research on the contribution of radiative forcing agents and mechanisms continues (Prather et al., 2012), and aside from claims by climate change skeptics, this aspect of anthropogenic versus natural contributions is no longer a concern in international negotiations.

3.1.2. Divergence between local origin and global effect of climate change

GHGs originate locally, but emissions affect atmospheric concentration jointly, leading to global impacts. In various policy contexts there is a need for responsibility to be quantified on a common scale so that mitigation and adaptation efforts reflect the relative degree of harm or benefit associated with the origin of the anthropogenic forcing agents, classified according to different criteria, such as economic (ex. per capita, individual enterprises, industries, economic sectors, producers and consumers), geographical (ex. regions, countries), or technological (ex. fossil fuel combustion, innovations). Yet because of the divergence between cause and effect, the question of responsibility for emissions as forcing agents is not a simple one.

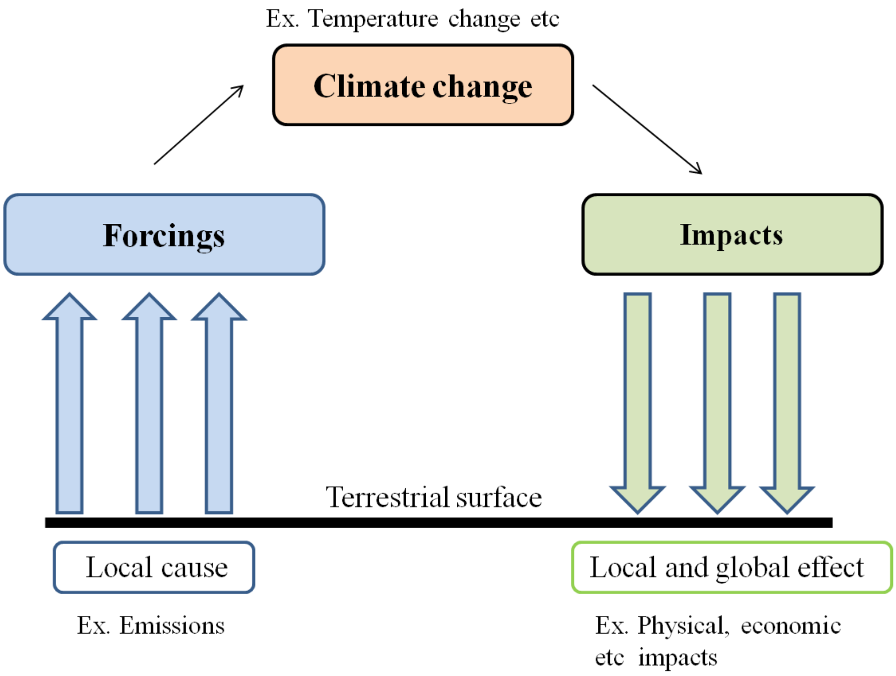


Figure 3- Local anthropogenic causes contrasted with global effect of climate change.

Source: Prepared by the author.

Up until now, there has been no international consensus on the adequate quantitative treatment of emission responsibility. The accurate assessment of responsibility is particularly relevant when one takes into consideration the fact that poor countries present the greatest vulnerability to climate change impacts (UNFCCC, 2006; World Bank, 2013).

During the first phase of the Kyoto Protocol (2008-2012), the concept of common but differentiated responsibility was defined in order to account for the historical responsibility of industrialized countries, but emission reduction targets assigned to each Annex I country were chosen based on subjective judgments concerning differences in the countries' economic development and energy matrices (UNFCCC, 2013). Developing countries classified as non-Annex I countries were not assigned emission reduction targets, as a form of guaranteeing these countries' equitable rights to a late development, yet absolute emission contributions from emerging countries such as Brazil, India and China are growing fast (although not on a per capita basis). According to the World Energy Outlook (WEO, 2012), the OECD's contribution of

CO_2 emissions relative to world emissions has been decreasing (53% in 1990, 40.9% in 2010, and forecasts of 34.5% in 2020 and 28% in 2035[24]).

Furthermore, in the Kyoto Protocol, the contribution of the different GHGs, which also reflects the degree of responsibility for emissions, was based on the GWP-100 metric, the limitations of which has been subject to much debate, as will be seen in later sections.

As already described in Section 2, the Brazilian Proposal addressed the question of national responsibility with the choice of a temperature change metric. The Proposal was not adopted by the Kyoto Protocol, but it contributed to the discussion of emission responsibility. The choice of temperature would allow for a more equitable differentiation of emission reduction targets in Annex I countries, flexibility in the use of the metric in policies, reduced mitigation costs and the inclusion of multiple gases without the need for the controversial GWP metric. The Proposal mentions that according to the emission forecast developed in the IPCC First Assessment Report (IPCC FAR), non-Annex I emissions would reach Annex I emissions by 2037, while according to the proposed temperature metric, non-Annex I countries would only cause the same temperature change as Annex I countries at a much later time, by 2162 (UNFCCC, 1997).

Historical and current responsibility for emissions is perhaps one of the most challenging and urgent questions in the context of international climate change negotiations. The failure of the first phase of the Kyoto Protocol in equitably assigning emission reduction targets to Annex I countries and the failure of negotiations aiming to include developing countries in legally binding mitigation efforts both attest to the urgency for a solution to the question of emission responsibility.

3.2. The diversity of impacts

A major challenge in the choice of an adequate metric is the diversity with which climate impacts manifest themselves, as can be seen from the climate change chain (described in Section 4.2), composed of elements which impact elements further along

[24] These values are for the WEO's New Policies Scenario, but values differ by less than 1% for the Current Policies Scenario, as world emissions rise at a similar rate to OECD emissions. New Policies scenario - 2020: 34,560 Mt (world), 11,920 (OECD); 2035: 37,037 Mt (world), 10,362 Mt (OECD).

in the chain as well as elements before them, through feedback mechanisms. How is a decision-maker able to judge which impact is most relevant to be used as a metric for a particular policy?

No metric is all-encompassing, so attributes and limitations of the metric must be clearly defined. Contexts must be well defined and informed compromises made. In a global stabilization scenario context, a reasonable choice for maximum impact tolerance might be the CO_2-equivalent concentration in the atmosphere (such as 450 ppm[25]), as long as underlying scenarios are well understood. In an emission reduction targets context, temperature change ceilings by a certain date might be used, taking into account the simplifications embodied in the choice of parameters such as climate sensitivity. When assessing the responsibility of countries, metrics appropriate on a common scale which encompasses multiple substances, regardless of their origin, are needed. Multi-gas equivalency emission metrics such as GWP and GTP might be chosen as a proxy for national impact on climate, but only with appropriate treatment of time and considerations about the equivalency of short-lived GHGs.

Metrics may also be chosen at the end of the chain, such as at the physical, biological and socio-economic levels, and at the mitigation level (elements 6-8 of Figure 4). At such levels, there is much diversity of impact manifestation, so these choices are subject to the specific situation in question. Indicators such as sea-level rise (projected to increase by 1.3 ± 0.7 mm per year) and ocean pH (forecast to diminish by 0.14 to 0.35 until the end of this century) are adequate for use in the assessment of the adaptability of island and coastal zones or in the study of coral reef survival, respectively, but have limited applicability in a broader policy context where common scales are needed (IPCC, 2007).

Policymakers wishing to assess economic impacts will have to choose metrics which take economic factors into account (Manne and Richels, 2001). The Global Damage Potential (GDP) measures the degree of harm caused by a GHG relative to the harm caused by the same mass of a reference GHG. In the case of specific mitigation strategies, the Global Cost Potential (GCP) measures the marginal cost of abatement of one GHG relative to a reference GHG (Gian-Kasper et al., 2009). The IPCC recommends further studies about metrics based on cost-benefit analysis and further

[25] ppm=parts per million. Ex. 379ppm of a GHG means 379 molecules of GHG per million molecules of dry air

investigation of the degree to which physical metrics may be used instead of more comprehensive metrics which measure economic impacts (IPCC, 2009).

It should also be mentioned that even at one particular level of impact, metrics can be defined differently, using absolute values or relative values (as in normalized metrics such as GWP and GTP), averages or ranges of values, rates of change or fixed values, integrated values or end-point values. One such example, at the level of radiative forcing, is the choice of an instantaneous or integrated metric. The IPCC has recommended that alternative metrics be developed beyond the current temperature increase ceilings, for policy targets such as the rate and integral of temperature change (IPCC, 2009).

Furthermore, beyond their diversity of manifestations, impacts have specific characteristics such as irreversibility and discontinuity, which must be taken into consideration when metrics are chosen. For instance, in agriculture some crops do not survive beyond certain temperature ceilings, but may be re-introduced if temperature is reduced. Yet in ecosystems certain changes are irreversible, such as the loss of biodiversity. Nobre et al. (2005, 2007) discuss the savannization of the Amazon. According to a study by Miles et al. (2004), a 2^{o}C increase in temperature, along with a reduction in soil humidity, may lead to the extinction of 43% of the 69 species of trees studied in the Amazon. As an example of discontinuity in impacts, with controlled irrigation and genetic manipulation, it is possible for some crops to tolerate an average temperature increase of up to 2-3^{o}C, beyond which the crop does not survive (Silveira, n.a.; Margulis and Dubeux, 2011)[26].

Summarizing, the context of a study or a policy defines the selection of the end-point indicator in the climate change chain to be used as metric. Because of the diversity of impacts, contexts must be carefully analyzed and all limitations of the metric addressed.

3.3. Practicality versus certainty

Metrics must be practical and user-friendly, and must lend themselves to easy incorporation into a legal framework. Decision-makers implementing policies should be able to use metrics in a flexible manner, so as to fulfill their obligations according to their individual constraints. Because of the large range of options available for the

[26] On the other hand, according to these authors, the productivity of certain crops may increase as temperatures rise.

assessment of impacts, and since metric choice and use require simplifications and are commonly presented to policymakers in a non-transparent way, assumptions which are fundamental in the determination of the metric are often concealed. As a result, not only policymaking but the implementation of policies can become unnecessarily challenging and inefficient.

Parameters used in the scientific community by climate specialists, such as numerical results derived from general circulation models (GCMs), have a limited scope for use in decision-making frameworks and are not viable for use in decision-making and legal frameworks (Fuglestvedt et al. ,2010). Such parameters, referred to as 'exact' indices by Shine et al. (2005), are more sophisticated and more accurate, as they are able to take into account different scenarios of background concentration of gases in the atmosphere, complex atmospheric chemistry and nonlinear relationships. The need for setting up a framework for the availability and correct use of exact indices presents a strong barrier to their acceptance (Shine et al., 2005), so easily formulated analytic forms are more likely to be accepted in policy contexts, even though they are likely to be less accurate. These simpler metrics present non-specialists with a basic understanding of the atmospheric system, in comparison to complex 'black-box' models (Fuglestvedt et al., 2010). Metrics can be derived from analytical models, or from model simulations, or from a combination thereof, but there is an inescapable trade-off between less precise but user-friendly metrics and more exact yet complex metrics.

In some cases, the need for practical metrics in negotiations should be overridden by the need for precision, yet there is no existing policy framework for special cases. In the case of savannization of the Amazon, the study by Miles et al. (2004) mentioned above, shows that a 2^{o}C increase is the limit of irreversible damage, yet local temperature forecasts in the Amazon are very uncertain. The preservation of the Amazon is at risk unless very precise global average temperature change metrics are available.

Another problem regarding the uncertainty of metrics in policy contexts is the need for updating. The GWP metric was first adopted as multi-gas equivalency metric by the Kyoto Protocol in 1997[27]. The GWP-100 values adopted correspond to the values published in the IPCC Second Assessment Report and are still in use today, even though many studies have been done updating mean radiative forcing values and atmospheric

[27]See Table 24 for the evolution of GWP values according to the IPCC Assessment reports.

lifetimes of the various GHGs, which have led to the constant evolution of GWP values. The consequences of the use of updated GWP values in the implementation of the Protocol, and any future agreements, need to be investigated. Furthermore, the fact that even a simple single-valued metric such as GWP cannot be kept up-to-date in policymaking, or the fact that the minimal implications of the use of old values are not investigated, indicates the additional difficulties which the adoption of more complex metrics would face.

Finally, it should be observed that although lack of precision of metrics in policy contexts is indeed a shortcoming, it might be preferable for policies to be based on uncertain metrics which are well-understood, the limitations of which have been exhaustively studied, than for more precise and complex metrics to be used incorrectly. Simple metrics can be used in a transparent manner and the consequences of their uncertainty in policies can be clearly understood and possibly even addressed, while the incorrect use of more complex metrics might never be identified.

3.4. Effect of local diversity on impacts

The origin of emissions affects the intensity of impacts in several ways. The same emissions can have different impacts based on local characteristics. These effects amplify the complexity of the issue of responsibility for emissions, due to the difficulty of comparing impacts on a common scale. According to IPCC recommendations, there should be a focus on studies assessing the regional differences in the relationship between emissions and impacts (IPCC, 2009).

First, the geographical origin of emissions can have different effects on the physics of climate change, such as in the case of short-lived species. The altitude of the emission of short-lived species, for instance, can have a markedly different effect on climate impacts and must be accounted for differently. This is particularly relevant in the aviation sector (see references for the aviation sector in Table 6).

Secondly, local technologic and economic characteristics affect the intensity of caused climate impacts. Different degrees of carbon intensity in the same sector of different countries, such as the power sector in a fossil-based economy such as China's compared to the same sector in Brazil, where the electricity matrix is predominantly renewable, lead to different global impacts per kWh generated.

Third, the vulnerability and capacity for adaptation to impacts is dependent on technological, economical and social development, as well as on geographical factors. Global metrics are not adequate for measuring local impact. In such cases cost of adaptation, often reported as percentage of GNP, may be a more adequate metric. The impact of a mitigation measure to reduce CH_4 emissions will affect an economy dependent on livestock and will not be captured by a multi-gas equivalency metric. Increases in temperature are not applicable on a common-scale when comparing regions at different latitudes. The risk of further desertification in sub-Saharan Africa from a 2^oC increase in average temperature, for instance, causes a more devastating impact than that caused by a 2^oC increase in northern latitudes. There have been many studies on the vulnerability of islands and coastal regions and how to best measure impacts of climate change in these regions according to a common scale (Rosman et al., 2009; Hanson et al., 2010; Margulis and Dubeux, 2011). Furthermore, the irreversibility of impacts, such as in changes in ecosystems, is highly sensitive to local temperature fluctuations and cannot be captured with metrics based on global average temperature change (Margulis and Dubeux, 2011).

3.5. Increasing relevance versus increasing uncertainty

There are two kinds of uncertainties which affect the precision of metrics.

The first kind is related to scientific choices, such as the development of the structure of the models chosen to represent physical systems, and the choice of parameters which are part of these models. Whether the model is analytical or a GCM, this kind of uncertainty reflects the limited knowledge about the physical system. In the case of the climate system, this uncertainty is present in parameters such as the atmospheric lifetime of GHGs, the climate sensitivity and the instantaneous radiative forcing of the various agents and mechanisms, as well as in processes such as the geochemical cycles, particularly the carbon cycle, thermal inertia of the ocean and feedback mechanisms.

As one advances along the climate change chain (described in Section 4.2), from climate forcing all the way through socio-economic impacts, the uncertainty in each element becomes incorporated into the uncertainty of the next element, especially in view of the fact that the output of one model is frequently used as the input for a model further along in the chain. Consequently, uncertainty is amplified as one moves along the chain. Nevertheless, parameters further along the chain have increased relevance and applicability for policymakers. The choice of metric must then necessarily address two different concerns, the level of uncertainty which is acceptable and the adequate relevance for the policy in question. Since these issues are not independent, a trade-off exists. As examples, at the far left of the chain, corresponding to emission sources, measurements can be very precise, but there is no clear relationship between emissions and climate change impact. In the middle of the chain, temperature change metrics depend on parameters such as the climate sensitivity and on processes involving the ocean, both of which introduce uncertainty. Yet global average temperature change is a highly relevant and tangible impact which can be used on a common scale across countries and across a large range of GHGs.

The second kind of uncertainty is related to subjective judgments which are necessarily part of policy development. As examples, at a physical level, the choice of a 100-year time-horizon for the GWP metric, or the choice of global metrics to assess local impacts, have implications on the assessment results; at an economic level, forecasts of future emissions necessarily include forecasts of economic growth, rates of technological change, choices of discount rates (Stern, 2006) and many other indicators, all of which have implications on impact assessment and mitigation costs.

Improvements expected in the yet unpublished IPCC Fifth Assessment Report (IPCC AR5) include a greater focus on studies reporting probability density functions for metrics, particularly for GWP and GTP, and a greater focus on short-lived pollutants, both of which address the first kind of uncertainty. A greater focus on various aspects of alternative metrics, including differentiating between short-term and long-term outcomes in policy contexts, a better treatment of temporal issues in metrics and the development of more encompassing metrics, will help address the second kind of uncertainty (IPCC, 2009).

3.6. Summary of challenges

It is paramount that chosen metrics precisely address the concerns of the policy in question, and that the policy be designed to adapt as well as possible to the available metrics, rather than the other way around. Over time, metric development has taken policy requirements into consideration, but there is a lag in this development, so policymakers must be sufficiently informed and open to suggestions about options before making final binding choices. For instance, in the Kyoto Protocol the multi-equivalency metric GWP-100 was adopted without specific concerns about the either the metric's temporal consequences or the ambiguity of the impact begin measured, even though limitations of the metric were understood at the time in the scientific community, and temperature changes had been proposed as an alternative, with the Brazilian Proposal. Only many years later have alternative metrics which address the treatment of time and the impact ambiguity more thoroughly been seriously addressed by the scientific community. In 2005, Shine et al. proposed the use of GTP for the first time, and the debate about alternative metrics is expected to be covered in greater depth in the IPCC's Fifth Assessment Report, to be released 17 years after the adoption of GWP-100 by the Kyoto Protocol.

Policymakers must be well-informed about state-of-the-art metrics, for which collaboration with the scientific community is indispensable. In particular, they should be aware of the degree of uncertainty present in metrics and in the parameters which are part of the models (Pielke, 2007). Scientists are responsible for producing clear guidelines listing the limitations of metrics and their suitability for application in different circumstances, and policymakers are responsible for seeking out these guidelines and adapting the design of their policies to best suit the current state of metric development. There are currently efforts underway to develop real-time tools that make results of climate change simulations transparent for policymakers (Climate Interactive, 2013).

Policymakers must have clear goals to guide the design of their policies. Value judgments will necessarily always play a role in policy negotiations, but a narrower focus on policy goals can help to minimize the role of arbitrary or biased value judgments. Article 2 of the UNFCCC states:

> The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner (UNFCCC, 1992).

The meaning of "dangerous anthropogenic interference" and the determination of the time frame is subjective and involves value judgments, and has been the continued subject of much debate. When climate change policies based on emission concentration stabilization scenarios associated with a supposedly tolerable temperature increase of at most 2°C above pre-industrial levels were proposed by the European Union (CONSILUM, 2005), the vague notion of 'dangerous' climate change was finally defined in an objective manner. The consequently more objective policy resulting from this narrowing of the initial 1992 objective could then aim at choosing a metric to achieve the emission concentration stabilization scenario, in this case a multi-equivalency metric.

Table 1 – Summary of challenges to be addressed by policymakers in choice of metrics.

	Challenge in choice of metric for impact assessment	Level of progress in research (IPCC, 2007)	Effect of challenge in policy context	Examples of issues to be dealt with by policymakers when addressing challenge
1	**Anthropogenic vs. natural causes**	High	Low	Addressing climate change skeptics.
2	**Local origin vs. global effect of impact**	Medium	Very high	Attribution of sectoral/regional national responsibility for emissions; selection of multi-gas equivalency metric; inclusion of non-Annex I countries in emission reduction targets; establishing sustainable developmental pathways for developing countries.
3	**Practicality vs. Precision**	Medium	Medium	Understanding of trade-offs in choice of end-point for impact (assessment of practicality, precision and relevance required by policy); determination of how comprehensive metric should be; should metric just account for physics of climate system, or should it include economic and social factors; assessment of local effects of uncertainty (irreversibility, discontinuity of impacts); identification of critical areas to be protected.
4	**Effect of local diversity on impacts**	Low	High	
5	**Relevance vs. Uncertainty**	Low	High	
6	**Temporal issues**	High	Very high	Design of short-term and long-term policies must take into account knowledge of when emissions take place, and when and for how long their impact is to be accounted for. The choice of time-horizon is critical, especially for emission mixes with short-lived GHGs. The choice of an end-point emission metric accounts for the target year of the policy, while an integrated emission metric does not.

Note: The levels of progress in research and the effect in policy contexts are based on the author's judgment.

Table 1 summarizes the general challenges facing by policymakers in the choice of metrics, as discussed in this chapter. It shows qualitative judgments on the progress of associated research on the various issues and the magnitude of these challenges, based on the IPCC Fourth Assessment Report, along with relevant examples. Temporal challenges will be addressed in the following chapter, when the GWP and GTP metrics are discussed in detail.

4. Methodology: climate change metrics

This chapter presents the methodology used to calculate the CO_2-equivalent emissions of the data scenarios (individual GHG emissions) presented in Chapter 5. The methodology consists of analytical formulations of the GWP and GTP metrics and was drawn from the literature.

The objective of this chapter is to present the analytical formulations of the metrics used in the study. They consist of equations with parameter inputs drawn from the literature, which are used to calculate the GWP and GTP values, as function of the time-horizon. This chapter focuses on discussing background material relevant to the derivation of the equations, such as climate models, the climate change chain, metrics in general, the concept of an emission metric, and finally focuses on the actual derivations. The values of the GWP and GTP functions are only presented in Chapter 7.

The formulation of the fixed and variable versions of the metrics are also presented in this chapter. The fixed metric refers to the classical manner in which GWP and GTP metrics are used for multi-gas equivalency calculations. The variable metric used here is an original contribution.

The structure of the chapter is as follows. First, a summary of the climate model hierarchy is presented (Section 4.1). Following is a simplified representation of the relationship between the highly complex climate processes, the climate change cause and effect chain (Section 4.2). After a brief discussion of the concept of metrics and parameters (Section 4.3), the general formulation of an emission metric is presented, leading up to the analytical formulations of GWP and GTP used in this study (Section 4.4). Finally, the fixed and variable forms of the metrics are presented (Section 4.5).

It should be noted that the analysis of the variations in the CO_2-equivalents requires a methodology of its own, presented in Chapter 7, but that methodology should not be confused with the emission methodology presented in this chapter. In other words, this study makes use of two different kinds of methodologies. The first, the emission methodology, is drawn from the literature, and with the exception of the formulation of the variable metric, does not constitute an original contribution. The methodology presented in Chapter 7, on the other hand, is an original contribution.

4.1. The climate model hierarchy

Climate models can be classified in a hierarchy, first described by Schneider and Dickinson in 1974 (Schneider and Dickinson, 1974). Energy Balance Models (EBMs) calculate the Earth's energy budget and constitute the most fundamental level of climate modeling. Based on parameters as solar radiation, albedo[28] and atmospheric absorption and radiative characteristics, EBMs calculate the Earth's average temperature. The earliest EBMs, "zero-dimensional" EBMs, considered the Earth to be a point mass in space and did not take into account the energy transfers on the surface of the Earth (Hartmann, 1994). One-dimensional EBMs include radiative transfers in latitude zones and two-dimensional EBMs include longitudinal transfers as well.

At the next level are the radiative-convective models (RCs), which consider vertical radiative transfers in the atmosphere, and two-dimensional models which consider vertical as well as meridional transfers.

The most complex models are Earth System Models, which contain the most detailed representations of atmospheric processes and their interactions with the biosphere, the cryosphere and the oceans. Global (or General) Circulation Models (GCMs) are one such example. They are three-dimensional simulations of not only radiative transfer, but of atmospheric and ocean circulation, including humidity, wind velocity and many other factors. They are very resource-intensive, for they break down the grid area of analysis into small 3D sections and simulate the interactions between them, producing a very large number of outputs and requiring expertise to analyze the results. They are used in conjunction with the less resource-intensive simpler models of lesser resolution. For example, EBMs and RC models can be used to check results of GCMs, while GCMs can be used to obtain parameters which are then in turn fed back as inputs into the simpler models. Upwelling-Diffusion EBMs (UD-EBMs) can be 'tuned'[29] to replicate the behavior of GCMs and the interaction of sub-systems. The simpler models can be used to investigate the sensitivity of parameters, for they can be run repeatedly, while it is not feasible to do so with GCMs (Edwards, 2010; Fuglestvedt et al., 2010).

[28] Albedo is defined as the fraction of incident radiation which is reflected back to the atmosphere. This consists of approximately 30% of the radiation incident on the Earth (30% of 342 Wm^{-2}, or 107 Wm^{-2}). This reflection occurs due to the presence of the clouds, aerosols and gases from the atmosphere, or from the terrestrial surface.

[29] Tuning a parameter involves adjusting it by changing the value of coefficients or the structure of an equation, so as to make the model agree more closely with observations or to produce better model results (Edwards, 2010).

Simple climate models can also be represented by analytical frameworks, consisting of equations easily solved without the use of computers, or numerically, if the equations are more complicated or involve multiple integrations. The simplest EBMs can be solved by hand. An impulse-response model has been developed to model the relationship between forcing agents and their response, as will be seen in the section about emission metrics (Section 4.4). For instance, atmospheric concentration can be modeled as a linear response to an emission pulse, radiative forcing can be modeled as a linear response to concentration changes, and temperature as a response to radiative forcing changes. These analytical models have been shown to produce reliable results when compared to simulation results from either UD-EBMs or GCMs, as they can also be 'tuned' to reproduce the results of the complex simulations. This study uses analytical impulse-response models.

The climate change cause and effect chain, presented in the next section, helps to understand the analytical impulse-response model, as the elements of the chain relate to each other sequentially.

4.2. The climate change cause and effect chain

The climate system can be represented as a cause and effect chain, shown in Figure 4.

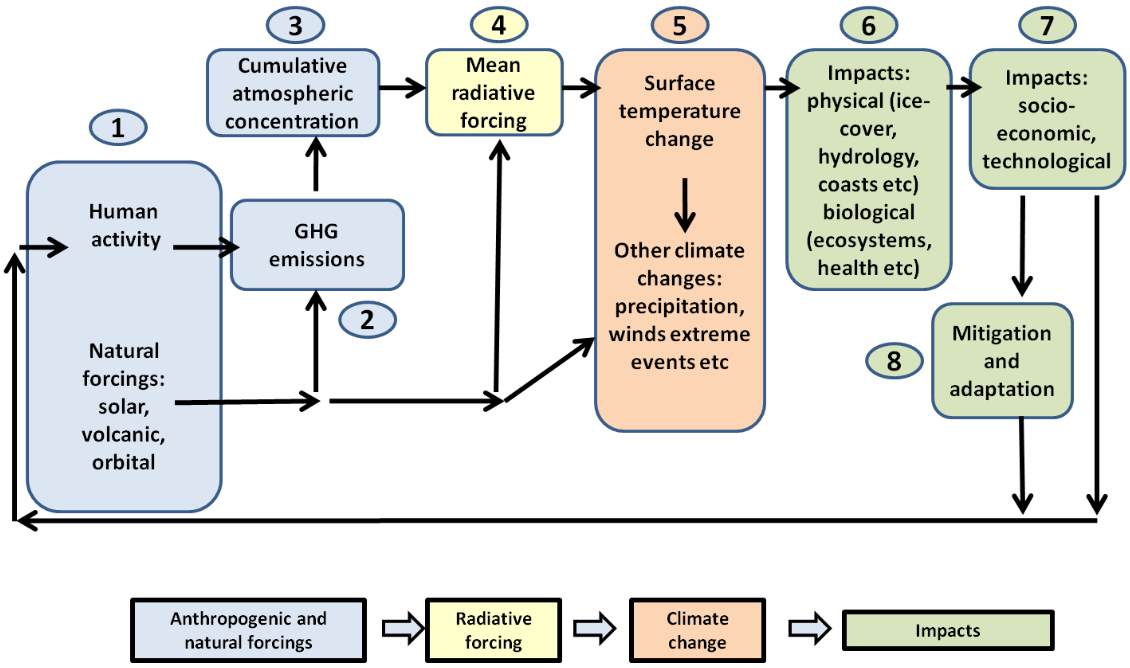


Figure 4 – Climate change cause and effect chain.

Source: Prepared by the author.

The forcing agents at the origin of the chain can be anthropogenic, comprising all human activity which affects climate, or natural, encompassing solar and volcanic activity, and the planet's orbital characteristics (element 1). The anthropogenic agents cause changes in greenhouse gas emissions and in other pollutants such as aerosols and ozone (element 2). Natural activity can also contribute to emissions, as in the case of volcanic aerosol emissions. Total emissions in turn determine the atmospheric concentration of all pollutants (element 3), as a result of the complex physical and chemical interactions in the atmosphere.

The cumulative atmospheric concentration of all pollutants, along with the other natural forcings, such as solar activity, lead to radiative forcing changes (element 4) and consequently to changes in surface temperature (upper part of element 5). The latter, along with natural forcings, determine the various climate elements: precipitation, wind, and the pattern and intensity of extreme weather events (lower part of element 5). Characteristics of clouds can in turn affect radiative forcing, exemplifying feedback mechanisms not accounted for in this simple representation. Similarly, temperature can affect emissions or the rate of atmospheric chemical reactions, which in turn determine the concentration of GHGs (ex.CH_4). Climate changes summarized by element 5 then cause physical impacts[30], such as changes in ice sheets and glaciers, oceans and sea-level, as well as biological impacts on ecosystems and human health (element 6). The physical impacts in turn cause socio-economic and technological impacts (element 7). There is some overlap between elements 6 and 7, as socio-economic impacts can include health impacts, accounted for in element 6 as well. The final link in the chain is the human response, namely adaptation and mitigation addressing the various impacts (element 8). The human response affects economic infrastructure, GDP energy intensity, the carbon intensity of energy, technological innovation, land-use changes, economic and population growth, behavioral changes and many others. The cycle is completed as these factors affect the human activity which originates the chain. Unger et al. (2010), for instance, look at economic sectors as drivers of radiative forcing, rather than the other way around.

4.3. Metrics and parameters

In the field of climate change studies, the term 'metric' is generally defined as a quantitative measure of the degree to which climate forcing agents, as classified in elements 1 through 4 of Figure 4 possess the potential to impact the climate system in some explicit manner. Fuglestvedt et al. (2010) use the term 'metric' to refer specifically to methods and tools which allow the impacts of emitted substances to be placed on a common scale.

In this study, the choice has been made to define the term 'metric' in the more general sense. It is used here as a synonym for 'climate change metric' and refers to climate change impact measurements which are useful for comparing any chosen impact on a common scale. Quantitative parameters which are candidates for metrics are drawn from the climate change chain described in Section 4.2. More parameters exist than

[30] In the literature, the term 'impact' can be used to refer to either forcings or to climate change impacts. This distinction is usually clear from the context. In this study, 'impact' will refer to exclusively to elements 6 or 7 of the chain, as shown in Figure 4

there are useful metrics. Parameters in the chain do not need to correspond exactly to a metric, but can be used as a component of the structure of the metric.

According to these definitions, examples of parameters in the chain are solar radiation, emissions, atmospheric lifetimes of GHGs, atmospheric concentration, instantaneous radiative forcing, global average surface temperature change, climate sensitivity, sea-level rise, extent of ice-coverage, frequency of extreme events, precipitation levels, loss of biodiversity and cost of adaptation as percentage of GDP. According to Edwards, parameters can be fixed, such as coefficients, or they may be mathematical functions containing both coefficients and dependent variables. Some fixed parameters, such as solar radiation, emissions and the concentration of a GHG in the atmosphere, can be obtained empirically through observations, but most variables of the climate system are generated through parameterization in modeling processes, exemplified by modeling of radiative forcing and clouds (Edwards, 2010).

All these are candidates for metrics in specific contexts. In this study, the parameters of interest are the ones that may be used as metrics to place physical impacts due to the anthropogenic emission of GHGs on a common scale. They will also be referred to as 'multi-gas equivalency metrics'. The two metrics that concern us here, GWP and GTP, are derived, respectively, from the parameters radiative forcing and temperature change.

4.4. Emission metrics

4.4.1. General formulation of an emission metric

Emission impacts vary because of two factors: GHGs have different lifetimes and different radiative efficiencies. Emission metrics were developed in the 1990's as indicators to compare emission impacts according to a common scale. They concern us here because the metrics AGWP and AGTP (absolute GWP and GTP, respectively) are special cases of this concept. Many comprehensive reviews of emission metrics exist in the literature. Shine et al. (2005) summarizes the limitations of the integrated radiative forcing-based metric GWP and introduces the alternative metric end-point metric GTP. An excellent review of radiative forcing and GWP issues, as well as alternative metrics, is addressed in Fuglestvedt et al. (2003). Fuglestvedt et al. (2010) discusses emission metrics from the point of view of the transport sector, which emits many different kinds of pollutants and is therefore illustrative of different issues relating to emission metrics.

Peters et al. (2011), discusses emission metrics from the point of view of life-cycle analyses, focusing on the importance of temporal issues for short-lived pollutants.

Kandlikar (1996) defines a general formula for an absolute emission metric AM_i. Suppose r is a baseline emission scenario where a perturbation to the climate system due to a component of type i occurs. This emission causes climate change $\Delta C_i(t)$ at time t. $I(t)$ is an impact function, which includes both damages and benefits, describing the impact caused by this climate change. The function $g(t)$ is a discounting function, which can, for instance, attribute more weight to recent impacts. For an end-point metric, such as GTP, where the impact assessment is made at a specific moment, the discount function is a Dirac delta function; for integrated metrics, such as GWP, the discount function is a step-function. AM_i can be written as a time-integrated difference between the impact of the scenario with emission and the baseline scenario, discounted appropriately (IPCC, 2007, in WG1, Section 2.10).

$$AM_i = \int_0^{\infty} \left[I\left(\Delta C_{r+i}(t)\right) - I\left(\Delta C_r(t)\right) \right] g(t)dt$$ **Equation 1**

If two perturbations are to be compared, the absolute metric for component i, AM_i can be normalized by the metric corresponding to another reference component j. GWP and GTP are examples of normalized metrics.

4.4.2. Instantaneous radiative forcing (ΔF)

Radiative forcing (ΔF) is a change in the net irradiance or a radiative imbalance at the Earth´s surface, caused by a natural or anthropogenic climate forcing agent. Radiative forcing is also referred to as 'climate forcing' in the literature and is used to assess natural and anthropogenic drivers of global warming, as was shown in Figure 4. It is a positive or negative incremental change, and will be described here as a time-dependent function $\Delta F(t)$, in Wm^{-2} units. The exact definition depends on where the change in irradiance is measured. For instance, high-latitude radiative forcings are more effective than low-latitude ones (Forster et al., 2007). Because of air motions and the resultant heat exchanges, the surface and the troposphere are thermodynamically coupled, and are considered a thermodynamic system, which responds to perturbations as a unit. Radiative forcing is therefore measured at the tropopause[31] (IPCC, 2007).

Two specific definitions of radiative forcing appear in the literature: instantaneous and integrated radiative forcing. According to the World Meteorological Organization (WMO, 2013), instantaneous radiative forcing is defined as the change in net radiative flux (including solar and infrared) at the tropopause due to climate forcing agents such as a change in solar radiation, in albedo, in the concentration of aerosols and GHGs, in volcanic activity etc. The IPCC defines radiative forcing in a similar fashion, as a perturbation of the energy balance of the surface-troposphere system, measured as the change in net (down minus up) irradiance at the tropopause, but stresses that the radiative forcing should only be measured after allowing for the stratosphere to re-adjust to a state of global mean radiative equilibrium, with surface and tropospheric temperatures and state held fixed at the unperturbed values. (IPCC, 2007; Zhang et al., 2011). Positive radiative forcing causes warming of the troposphere-surface system, while negative radiative forcing causes cooling.

The concept of radiative forcing is practically appealing because of the assumption that there exists a simple relationship (the impulse response model mentioned in Section 4.1) between global mean radiative forcing and the global mean increase in surface temperature, approximately true for radiative forcings caused by different forcing drivers, and governed by the climate sensitivity parameter (Forster et al., 2007).

The formulation for instantaneous radiative forcing is a special case of the emission metric defined in Equation 1. Because the metric is instantaneous, the integral in that equation is not needed. The discount function g(t) becomes a Dirac delta function. The climate change perturbation ΔC is an evolving emission pulse E(t) and the impact I is the radiative forcing resulting from these emissions. The final formulation is given by a convolution of the emissions with an impulse response function $R_x(t)$, which accounts for the residence time of the gas in the atmosphere, or lifetime of the gas. In other words, the function $R_x(t-t')$ is the impulse response at time t of an emission forcing $E(t')$ at time t'. The full radiative forcing at a point t in time depends on the emissions

[31] The tropopause is the transition boundary between the troposphere and the stratosphere (troposphere: 6-20 km above surface of earth, region where almost all weather occurs; stratosphere: region from top of troposphere to 50 km) (NOAA, 2103)

and its associated response at each moment in the period, hence the integral[32]. The proportionality constant A_x is the instantaneous or specific radiative forcing per kg, with unit $Wm^{-2}kg^{-1}$.

The definition of radiative forcing for evolving emissions of a component x in the continuous domain is then a special case of Equation 1 (Peters et al., 2011):

$$\Delta \boldsymbol{F_x}(\boldsymbol{t}) = \mathrm{A_x} \int_0^t \mathrm{E}(\boldsymbol{t'}) \boldsymbol{R_x}(\boldsymbol{t} - \boldsymbol{t'}) \mathrm{d}\boldsymbol{t'}$$ **Equation 2**

The impulse response $R_x(t)$ for a unit pulse can be expressed as a simple exponentially decaying function for many gases, or as a summation of exponentials if the gas has more than one decay time, such as CO_2. The impulse response for CO_2 is based on the Bern carbon cycle model, which takes into account carbon sinks (Joos et al., 2001). The decay times are given by parameters α_i.

$$\boldsymbol{R_x}(\boldsymbol{t}) = \sum_{i=1}^{K} \boldsymbol{a_i} \boldsymbol{e}^{\frac{-t}{\alpha_i}}$$ **Equation 3**

This formulation of the radiative forcing for a unit 1kg pulse (as opposed to evolving emissions) is important for it is used in the formulation of GWP, presented in the next section. For a unit pulse, there is no convolution, so the integral in Equation 2 disappears:

$$\Delta \boldsymbol{F_x}(\boldsymbol{t}) = \mathrm{A_x}\ \boldsymbol{R_x}(\boldsymbol{t})$$ **Equation 4**

Two special cases for a unit pulse should be noted.

---

32 Expressing the radiative forcing at moment t in terms of a discrete Delta function shows clearly how the emission decay is discounted. If R(t) is a decaying exponential, for instance, we see how the emissions further back in time relative to moment t weigh less than the emission closer to time t:

$$\Delta F(t) = A \sum_{t'=0}^{t} E(t')R(t-t') = A\{E(0)R(t) + E(1)R(t-1) + \cdots + E(t)R(0)\}$$

First, the special case of a unit emission pulse for a gas with just one decay time α_x, such as CH_4, the impulse response $R_x(t)$ is a simple decaying exponential and the radiative forcing Equation 2 simplifies to:

$$\Delta \boldsymbol{F_x}(\boldsymbol{t}) = A_x \, e^{-\frac{t}{\alpha_x}} \qquad \textbf{Equation 5}$$

Second, the special case of a unit emission pulse for CO_2, which can be approximated by 4 decay times (Lashof and Ahuja, 1990; Forster et al., 2007; Fuglestvedt et al., 2010), the impulse response $R_x(t)$ has 4 terms and Equation 2 simplifies to[33]:

$$\Delta \boldsymbol{F_x}(\boldsymbol{t}) = A_x \left[\boldsymbol{a_0} + \sum_{\boldsymbol{i=1}}^{\boldsymbol{3}} \boldsymbol{a_i} \boldsymbol{e}^{\frac{-\boldsymbol{t}}{\boldsymbol{\alpha_i}}} \right] \qquad \textbf{Equation 6}$$

The parameters in this equation are given in Table 3, shown in Section 4.4.4.

4.4.3. Integrated radiative forcing (iΔF)

Integrated radiative forcing considers the effect of radiative forcing for a time period and in the literature is usually presented as the backward-looking radiative forcing relative to pre-industrial times. Forward-looking radiative forcing can be used to evaluate the impact of climate change on future emissions scenarios, or the impact of current emissions.

In the context of Kandlikar's (1996) generalized emission metric concept (Equation 1), impact I is the radiative forcing for a climate perturbation of 1kg of the GHG released into the atmosphere, and the discount function is a unit function (g(t) =1 for duration of time-horizon and g(t) = 0 thereafter):

$$\mathbf{i\Delta F_x(t)} = \int_0^t \mathbf{\Delta F_x(t')} \, \mathbf{dt'} \qquad \textbf{Equation 7}$$

Once again as a preview of the formulation of GWP, the same two special cases should be noted.

First, for the special case of a unit pulse of a gas with a simple decay time (just one decay time α) this formulation becomes the definition of AGWP for gases such as CH_4.

[33] Based on this model, Wallington et al., 2011 shows that after 5, 20, 50 and 100 years, a reasonable approximation for the fraction of CO_2 which remains in the atmosphere is 75, 54, 41 and 33%.

Inserting into Equation 7 the definition of radiative forcing as given by Equation 5, we obtain:

$$\mathbf{i\Delta F_x(t)} = \int_0^t \boldsymbol{A_x} e^{-\frac{\boldsymbol{t'}}{\alpha_x}} \,\mathrm{d}\mathbf{t'} \qquad \textbf{Equation 8}$$

Second, for the special case of a unit emission pulse for CO_2, inserting into Equation 7 the definition of radiative forcing as given by Equation 6, we obtain the following, which is the definition of AGWP for CO_2:

$$\Delta \boldsymbol{F_x}(\boldsymbol{t}) = \int_{\mathbf{0}}^{\boldsymbol{t}} \boldsymbol{A_x} \left[\boldsymbol{a_0} + \sum_{\boldsymbol{i}=\mathbf{1}}^{\mathbf{3}} \boldsymbol{a_i} \boldsymbol{e}^{\frac{-\mathbf{t'}}{\boldsymbol{\alpha_i}}} \right] \mathrm{d}\mathbf{t'} \qquad \textbf{Equation 9}$$

4.4.4. Global warming potential

The GWP was first defined by Lashof and Ahuja (1990) as an index to aid the design of cost-effective policies. This metric is a measure of the relative radiative forcing, after a certain time period, of a pulse emission of the gas released at some point in time compared to the radiative forcing of the same unit mass of CO_2, and is used as a multiplier in estimating the CO_2 equivalence of non-CO_2 emissions.

The emission metric absolute global warning potential (AGWP) of a single gas, as first developed by Lashof and Ahuja (1990), is a special case of the Kandlikar's general formulation for one emission component, as given by Equation 1. Although the practical use of this formulation involves many difficulties, such as the definition of an appropriate impact function, baseline scenarios and discount functions (IPCC AR4, Shine, Berntsen, et al., 2005), Lashof and Ahuja (1990) simplified the formulation by narrowing the definition and making certain assumptions.

There are two simplifying assumptions made in the development of the GWP metric.

In a real scenario, the instantaneous or specific radiative forcing per kg of component x, A_x, is dependent on the gas concentration and on the concentration of other gases in the atmosphere, the first simplifying assumption (Shine, Fuglestvedt, et al., 2005). In the GWP ideal scenario, the specific radiative forcing is a constant. The climate response is therefore simplified and is considered equal for the various complex radiative forcing mechanisms (IPCC, 2007).

The second major assumption in the development of the GWP metric consists of the assumption that the GHG's lifetime is constant, when in fact it depends on the concentration of the gas itself and on the concentration of other gases (Shine, Fuglestvedt, et al., 2005; IPCC, 1995; Wuebbles et al., 1995; Fuglestvedt et al., 2003).

In this study, the formulation used for the calculation of the AGWP is that of Forster et al., (2007), used by the IPCC in the Fourth Assessment Report (IPCC, 2007). It is based on Lashof and Ahuja's original assumptions and formulation[34].

According to these assumptions, the AGWP is defined as the change in the instantaneous radiative forcing, in units of W/m^2, after a certain time-horizon TH, caused by a unit mass or pulse emission of 1kg of the gas released at t=0. The baseline scenario *r* is an ideal scenario where there are no emissions, and the discount function has a value of 1. By integrating over this specified time period, the AGWP takes into account the decay of the gas in this period, which results in a decreasing radiative forcing impact as the gas molecules are broken down. The following equation is similar to Equation 7:

$$AGWP_x(TH) = \int_0^{TH} \Delta F_x\ (\boldsymbol{t})dt$$ **Equation 10**

For a well-mixed gas x with a constant lifetime, the gas concentration is assumed to decay exponentially, so the AGWP is defined as the following, and is similar to Equation 8. It should be noted that the decay parameter α_x for a GHG x, if it accounts for feedbacks in the climate system, is more accurately called the adjustment time, rather than the lifetime of the GHG (Shine et al., 2007). Adjustment times are outputs of more complex models and are used as inputs in the simpler analytical models, as was explained in Section 4.1.

$$AGWP_x(TH) = \int_0^{TH} A_x\ e^{-\frac{t}{\alpha_x}} dt\ =\ A_x\ \ \alpha_x \left[1 - e^{-\frac{TH}{\alpha_x}}\right]$$ **Equation 11**

where

[34] For a comprehensive description of GWP, see the IPCC Fourth Assessment Report, WG1, Chapter 2 (IPCC, 2007).

TH = time-horizon

A_x= specific radiative forcing for gasx

α_x= adjustment time for gas *x*

In this study, the parameters used for CH_4 and N_2O are the following:

Table 2 - Parameters for AGWP of CH_4 and N_2O.

	CH_4	**N_2O**
A_x (Wm^{-2} kg^{-1})	$1.82*10^{-15}$	$3.88*10^{-13}$
α_x (dimensionless)	12	114

Source: Forster et al., 2007.

The atmospheric decay of the reference gas CO_2 is more complex (see Equation 6). The AGWP of CO_2 is defined as the following, and is similar to Equation 9:

$$AGWP_{CO_2}(TH) = \int_0^{TH} A_{CO_2}\left[a_0 + \sum_{i=1}^{3} a_i e^{\frac{-t}{\alpha_i}}\right] dt \qquad \textbf{Equation 12}$$

where

TH = time-horizon

A_{CO2}= specific radiative forcing for *CO2* CO_2

α_i (for i =1,2,3) = adjustment times in *CO2* CO_2 response function

a_i (for i =0,1,2,3) = parameters inCO_2 *CO2* response function

In this study, the parameters used for CO_2 are the following:

Table 3 – Parameters for AGWP of CO_2.

		i =0	i =1	i =2	i =3
A_{CO2} (Wm^{-2} kg^{-1})	$1.8088*10^{-15}$	-	-	-	-
α_i (years)	-	-	172.9	18.51	1.186
a_i (dimensionless)	-	0.217	0.259	0.338	0.186

Source: Forster et al., 2007.

The dimensionless GWP for a fixed time-horizon TH for gas x can then be defined as the ratio of the AGWPs of two gases, where the one in the denominator is chosen as a standard. CO_2 is chosen as a standard for GWP reference.

$$GWP_x(TH) = \frac{AGWP_x(TH)}{AGWP_{CO_2}(TH)}$$ **Equation 13**

In this study, the formulation of GWP defined in Section 4.5.1 will be referred to as *fixed GWP*, so as to make a clear distinction between the traditional GWP and the dynamic or variable GWP, to be defined in Section 4.5.2.

4.4.5. Global Temperature Potential

Much research has been done on temperature change as a metric. In this section the evolution of the GTP metric will be traced, from Shine's original models (Shine, Fuglestvedt, et al., 2005), culminating in Boucher and Reddy's model (Boucher and Reddy, 2008), used in this study. This cumulative presentation, in which we first present Shine's models, allows us to discuss the limitations of the simpler models and, most importantly, justify the use of the more complex model as the GTP metric used in this study. It also allows the general characteristics of the temperature change metric to be more readily understood, as Boucher and Reddy's model has a complex formulation.

While GWP is based on the evolution of radiative forcing due to an emission pulse summed over a fixed period of time, GTP it is one step beyond GWP in the climate change chain as it accounts for a specific climate response, the change in surface temperature at a fixed point in time. GTP thus depends on how fast the climate responds to radiative forcing as it evolves. This dependence is accounted for in the climate sensitivity parameter. It is also sensitive to the system heat capacity. The formulation of GTP is more complex than that of GWP and embeds more uncertainty than GWP because of these two parameters. But its main advantage is that, unlike GWP, it estimates an unambiguous climate response. Additionally, it specifies the climate response at a specific point in time, while GWP represents the sum of undiscounted impacts over a fixed time-horizon.

Characteristics of the GTP variants, as well as of GWP, are contrasted and summarized in Section 7.5.

4.4.5.1. Formulation of GTP according to Shine et al., 2005

The GTP metric was originally proposed by Shine, Fuglestvedt, et al., 2005 as an alternative metric to the GWP. The authors built upon an already-existing framework developed by Meira Filho and Miguez, 2000, as well as other authors, whose analysis was not tested through numerical results. Like the GWP metric, the metric Shine et al. (2005) proposed was based on a simple climate model and expressed in a simple analytical form, but went beyond the previous work by testing the metric against an energy balance model.

The formulation for temperature change is another special case of the emission metric defined in Equation 1 and parallels the formulation of Equation 2. The climate change perturbation ΔC is an evolving radiative forcing ΔF(t) and the impact I is the temperature change resulting from this forcing. The discount function g(t) becomes a Dirac delta function, so that the final formulation is given by a convolution of the radiative forcing with an impulse response function R(t). The full temperature change at a point t in time depends on the radiative forcing and its associated response at each moment in the period, hence the integral[35].

[35] Here is the temperature change expressed in terms of a discrete Delta function, in parallel with the expression for radiative forcing, showing clearly how the radiative forcing is discounted. The function R(t-t') is the temperature impulse response at time t due to a radiative forcing $\Delta F(t')$ at time t':

$$\Delta T(t) = \frac{1}{C}\sum_{t'=0}^{t} \Delta F(t')R(t-t') = \frac{1}{C}[\Delta F(0)R(t) + \Delta F(1)R(t-1) + \cdots + \Delta F(t)R(0)]$$

The most general definition of absolute GTP in the continuous domain (Shine et al., 2005; Fuglestvedt, 2010), and from which all others are derived, parallels Equation 2:

$$AGTP(t) = \frac{1}{C}\int_0^t \Delta F(t)R(t-t')dt' \qquad \textbf{Equation 14}$$

Based on this general formulation, Shine, Fuglestvedt, et al. (2005) demonstrate the formulation of two variants GTP_P and GTP_S , developed depending on how the radiative forcing and the response function are defined. The impulse response function R(t) can be defined as a simple decaying exponential, which is the basis for the authors' two models, or by a more complex summation of decaying exponentials, which is Boucher and Reddy's approach. The models by Shine, Fuglestvedt, et al. (2005) depend on whether the emission is a one-time pulse or a sustained emission pulse, which lead to a different definitions of radiative forcing. The radiative forcing must also be defined separately for non-CO_2 GHGs and CO_2 (a simple decaying exponential for the former and a summation of decaying exponentials for the latter, as already discussed in Section 4.4.2). The radiative forcing models and the exponential response function used to develop the variants are summarized in Table 5.

Simplest temperature change model

Before presenting their two variants, Shine, Fuglestvedt, et al. (2005) present the simplest temperature change model, the globally averaged energy balance model described by several authors (Schneider and Dickinson, 1974; Hartmann, 1994). This simple model assumes that the climate system can be described as a first-order linear system, regarded as a single entity with a heat capacity given by C (in simple models, this heat capacity can be taken to be that of mixed-layer ocean).

$$C\frac{d\Delta T(t)}{dt} = \Delta F(t) - \frac{\Delta T(t)}{\lambda} \qquad \textbf{Equation 15}$$

where

ΔT(t) = surface temperature change at time t (K)
ΔF(t) = radiative forcing at time t (Wm^{-2})
C = heat capacity of system (Wm^{-2}/K)
λ = climate sensitivity (K /(Wm^{-2}))

If radiative forcing is assumed to be constant, the analytical solution is simple. The response function is assumed by Shine, Fuglestvedt, et al. (2005) to be a simple decaying exponential dependent on two variables, the climate sensitivity and the heat capacity of the system. The expression for ΔT(t) is given by either solving Equation 15, or by inserting $\Delta F(t) = \Delta F$ and $R(t) = e^{\frac{-t}{\lambda C}}$ into Equation 14 and solving it:

$$\Delta T(t) = \frac{1}{C}\int_0^t \Delta F\, e^{\frac{t'-t}{\lambda C}}\, dt' = \lambda \Delta F\left(1 - e^{\frac{-t}{\lambda C}}\right) \qquad \textbf{Equation 16}$$

This formulation of surface temperature based on this simple model with a constant radiative forcing illustrates the importance of the time-scale given by the product $\tau = \lambda C$ in the GTP concept, as pointed out by Fuglestvedt (2010). This time-scale determines the time for the system to respond to the radiative forcing. For a short-lived gas with a small life-time relative to λC, the climate system will not have time to respond to the radiative forcing before the gas has decayed. For a long-lived gas, the system will have time to respond fully (Wigley, 2005). After stabilization, since $\lim_{t\to\infty} \Delta T(t) = \lambda \Delta F$, temperature change in this simple model is proportional to radiative forcing, with the climate sensitivity as the proportionality parameter.

Formulation of $AGTP_P$ and $AGTP_S$ models

Shine, Fuglestvedt, et al. (2005) proposed two variants or models of GTP: for a pulse emission of a gas, referred to as GTP_P, where the metric gives the temperature change at the target year due to a unit mass emission of the gas; and for sustained emissions, referred to as GTP_S. Comparison with energy balance models show that the GTP_P metric is more accurate for short-lived gases than for long-lived ones, while GTP_S is accurate for a wide range of GHG lifetimes. The authors recommend the use of GTP_S as a new metric to substitute for GWP. For time-horizons of 100 years or longer GTP_S was shown to be similar to GWP, so it can be argued that there is little advantage to substituting GWP with GTP_S. But GTP_S differs from GWP for short time-horizons, particularly for short-lived gases, and it has a less ambiguous interpretation than GWP. GTP_P is more useful for application in policy scenarios that need to consider varying emissions, rather than the less realistic sustained emission scenarios.

The GTP for a GHG *x* is normalized in reference to CO_2, as in the definition of GWP:

$$GTP_x(TH) = \frac{AGTP_x(TH)}{AGTP_{CO_2}(TH)}$$ **Equation 17**

Following we present the formulation of $AGTP_P$ and $AGTP_S$ for non-CO_2 GHGs and CO_2. For each of the 4 formulations obtained from Equation 14, the response function is the same, and there are 4 different variations for the radiative forcing.

To formulate $AGTP_P$ for both non-CO_2 and CO_2, the authors use a simple decaying exponential for the response function, as the climate system is assumed to be a first-order linear system[36]:

$$R(t) = e^{\frac{-t}{\lambda C}}$$ **Equation 18**

For non-CO_2, the radiative forcing for an emission pulse of GHG *x* is the same as Equation 5:

$$\Delta F(t) = Ae^{-\frac{t}{\alpha}}$$ **Equation 19**

where α is the lifetime of the gas and A its specific radiative forcing.

Inserting Equations 18 and 19 into Equation 14, we obtain for GHG *x*:

$$AGTP_P^x(t) = \frac{A_x}{C\left(\frac{1}{\tau} - \frac{1}{\alpha_x}\right)}\left[e^{-\frac{t}{\alpha_x}} - e^{\frac{-t}{\tau}}\right] \; for \; \tau \neq \alpha_x$$ **Equation 20**

where $\tau = \lambda C$.

For CO_2, the radiative forcing is:

$$\Delta F(t) = A\left[a_0 + \sum_i a_i e^{-\frac{t}{\alpha_i}}\right]$$ **Equation 21**

where a_i are dimensionless parameters.

---

[36] The assumption that the climate system can be approximated by first-order linear systems has been shown to result in good approximations when compared to observational data. Parameters which are inputs in these simple models, such as the climate sensitivity and the specific heat of the climate system, are the subject of much research and are updated by means of GCMs, thus continuously improving and validating the models.

Inserting Equations 18 and 21 into Equation 14, we obtain:

$$AGTP_P^{CO2}(t) = \frac{A_x}{C}\left\{\tau a_0\left[1 - e^{-\frac{t}{\tau}}\right] + \sum_i \frac{a_i}{\left(\frac{1}{\tau} - \frac{1}{\alpha_x}\right)}\left[e^{-\frac{t}{\alpha_x}} - e^{\frac{-t}{\tau}}\right]\right\} for\ \tau \neq \alpha_x$$ **Equation 22**

To formulate GTP_S for both non-CO_2 and CO_2, Shine assumes that the response function is once again a simple decaying exponential, as for GTP_P (see Equation 18)

For non-CO_2, the radiative forcing for a sustained emission pulse is:

$$\Delta F(t) = A\alpha\Delta S(1 - e^{-\frac{t}{\alpha}})$$ **Equation 23**

where ΔS is the constant value of the sustained emission in kg.

Inserting Equations 18 and 23 into Equation 14, we obtain:

$$AGTP_S^x(t) = \frac{\alpha_x A_x}{C}\left\{\tau\left[1 - e^{\frac{-t}{\tau}}\right] - \frac{1}{\left(\frac{1}{\tau} - \frac{1}{\alpha_x}\right)}\left[e^{-\frac{t}{\alpha_x}} - e^{\frac{-t}{\tau}}\right]\right\}$$ **Equation 24**

$$for\ \tau \neq \alpha_x$$

For CO_2, the radiative forcing is:

$$\Delta F(t) = A.\int_0^t \Delta S(t')\left(a_0 + \sum_i a_i e^{-\frac{t}{\alpha_i}}\right) dt'$$ **Equation 25**

Inserting Equations 18 and 25 into Equation 14, , we obtain[37]:

[37] It should be noted that AGTP Equation 20, Equation 22, Equation 24 and Equation 26 reduce to a simpler form when τ=αx and can be found in Shine, Fuglestvedt, et al., 2005.

$$AGTP_S^{CO2}(t) = \frac{A_{CO2}}{C}\left\{a_0 t\tau - a_0\tau^2\left[1 \; - e^{\frac{-t}{\tau}}\right]\right.$$

$$\left. + \sum_i \alpha_i\, a_i\left[\tau\left(1 \; - e^{\frac{-t}{\tau}}\right) - \frac{1}{\left(\frac{1}{\tau} - \frac{1}{\alpha_x}\right)}\left[e^{-\frac{t}{\alpha_x}} \; - e^{\frac{-t}{\tau}}\right]\right]\right\}$$ **Equation 26**

$$for\ \tau \neq \alpha_x$$

4.4.5.2. Formulation of GTP according to Boucher and Reddy

Since Shine, Fuglestvedt, et al. (2005) proposed the original GTP, several variants of GTP of increasing complexity have been suggested, as more sophisticated climate models are taken into account. Shine et al., 2007 studied the effect of different climate models on the GTP metric, and showed that large errors resulted if the climate system's long-term memory, such as the deep ocean, was not taken into account (Fuglestvedt, 2010). The GTP variant used in this study[38], that of Boucher and Reddy (2008), simulates the deep ocean more realistically, and is described in Fuglestvedt (2010). It is based on the general definition of AGTP given by Equation 14.

The definitions for the radiative forcing here are the same as those considered by Shine, Fuglestvedt, et al. (2005) for a unit pulse emission (Equation 19 for non-CO_2 GHGs and Equation 21 for CO_2).

The temperature impulse response function to the radiative forcing climate perturbation is a simply decaying exponential, given by Equation 18, dependent on the climate sensitivity and the system heat capacity, where the 'system' is considered to be the ocean. Here, the temperature impulse response function takes into account a more sophisticated model of the ocean. It achieves this by including two terms in the function: an approximation of the response of the ocean mixed-layer (the first term for j=1) and the deep ocean (the second term for j=2). There are two climate sensitivity values, c_1 and c_2, which when added give us the total climate sensitivity. The parameters in this formulation were tuned with GCM results and are shown in Table 4.

[38] The CICERO model used in this study solves the Boucher and Reddy equations.

$$R(t) = \sum_{j=1}^{2} \frac{c_j}{d_j} e^{-\frac{t}{d_j}}$$ **Equation 27**

where c_j are climate sensitivity parameters and d_j are time parameters.

Inserting this improved impulse response formulation and the unit emission pulse formulations used by Shine, Fuglestvedt, et al. (2005) for radiative forcing (Equation 20 for non-CO_2 GHGs and Equation 22 for CO_2) into the general definition of AGTP (Equation 14), we obtain for non-CO_2 GHGs and CO_2, respectively:

$$AGTP^{x}(t) = \sum_{j=1}^{2} \frac{A_x \ \alpha c_j}{\alpha - d_j} \left[e^{-\frac{t}{\alpha_x}} - e^{-\frac{t}{d_j}} \right] for\ \alpha \neq d_j$$ **Equation 28**

$$AGTP^{CO2}(t) = A_{CO2} \left\{ \sum_{j=1}^{2} a_0 c_j \left[1 - e^{-\frac{t}{d_j}} \right] + \sum_{i=1}^{3} \sum_{j=1}^{2} \frac{a_i \alpha_i c_j}{\alpha_i - d_j} \left[e^{-\frac{t}{\alpha_j}} - e^{-\frac{t}{d_j}} \right] \right\}$$ **Equation 29**

Parameters are listed in Table 4:

Table 4 - Parameters for AGTP of CH_4 and N_2O.

	j=0	j=1	j=2	j=3
a_i (dimensionless)	0.217	0.259	0.338	0.186
α_i (years)	-	172.9	18.51	1.186
c_j ($K(Wm^{-2})^{-1}$)	-	0.631	0.429	-
d_j (years)	-	8.4	409.5	-

Source: Fuglestvedt et al., 2010

4.4.5.3. Summary of GTP formulations

The table below summarizes the assumptions made for the radiative forcing and the temperature impulse response used in the formulation of the AGTP models.

Table 5 – Radiative forcing and impulse response models leading to AGTP models.

	$\boldsymbol{\Delta T(t)}$	$\boldsymbol{\Delta F(t)}$	$\boldsymbol{R(t)}$
Simplest model	**Non-CO_2 or CO_2** Equation 16	Constant ΔF	$e^{\frac{-t}{\lambda C}}$
Pulse emission ($AGTP_P$) (Shine, 2005)	**Non-CO_2** Equation 20	$Ae^{-\frac{t}{\alpha}}$	$e^{\frac{-t}{\lambda C}}$
	CO_2 Equation 22	$A\left[a_0 + \sum_i a_i e^{-\frac{t}{\alpha_i}}\right]$	
Sustained emission ($AGTP_S$) (Shine, 2005)	**Non-CO_2** Equation 24	$A\alpha\Delta S(1 - e^{-\frac{t}{\alpha}})$	
	CO_2 Equation 26	$A\int_0^t \Delta S(t')\left(a_0 + \sum_i a_i e^{-\frac{t}{\alpha_i}}\right) dt'$	
Pulse emission (Boucher & Reddy, 2008)	**Non-CO_2** Equation 28	$Ae^{-\frac{t}{\alpha}}$	$R(t) = \sum_{j=1}^{2} \frac{c_j}{d_j} e^{-\frac{t}{d_j}}$
	CO_2 Equation 29	$A\left[a_0 + \sum_i a_i e^{-\frac{t}{\alpha_i}}\right]$	

Source: . Prepared by author, based on Shine, Fuglestvedt, et al., 2005; Fuglestvedt et al., 2010.

4.4.6. GWP limitations and advantages

The GWP metric was not designed for any specific policy goal, yet its simplicity and small number of input parameters led to the adoption of the GWP with a 100-year time-horizon by the Kyoto protocol of the UNFCCC. GWP's main advantage is its current role in policy negotiations as a simple tool which provides a common quantitative scale for multi-gas comparisons. It depends on only three parameters: the instantaneous radiative forcing of the gas, the lifetime of the gas and a chosen time-horizon. Estimating the impact of a non-CO_2 gas requires nothing more than applying to emissions a well-known multiplicative factor, and policymakers do not need to consider the parameters. It is one of the few metrics which is accepted in legal contexts, as can be seen in Article 5.3 of the Kyoto Protocol (UNFCCC,1998).

Radiative forcing, upon which GWP is based, and surface temperature change, upon which GTP is based, are the first and last links of the climate change chain which are currently considered viable for quantification of impact on a common scale (Fuglestvedt, 2010). Atmospheric concentration of individual gases, the link in the chain before radiative forcing, does not provide us with a measure of their climate damage. Parameters representing physical, biological and socio-economic impacts at the end of the chain are the most relevant, but these metrics must incorporate complex impact criteria, as argued by the first group in O'Neill's (2003) classification, discussed below. Therefore quantitative metrics currently chosen for determining multi-gas equivalency from the climate change chain are based on radiative forcing or temperature change, parameters taken from the middle of the climate change chain.

The debate on GWP limitations started in the 1990's, when the idea of GWP as a political instrument was still being consolidated (De Cara et al., 2006).

According to O'Neill (2003), the debate in the literature concerning the GWP metric can be classified into three main views.

In the first view, purely physical metrics should incorporate the economic dimension if they are to serve as a tool for the implementation of cost-effective policies. Economists concerned about climate change questioned early on in the debate the validity of GWP as a tool for equivalency of impact (Eckhaus, 1992; Schmalensee, 1993; Reilly and Richards, 1993). They claimed that comparisons based on purely physical criteria would lead to distortions in economic analyses and in the development of objective emission reduction targets. This issue is still being extensively studied (Bradford, 2001; Manne and Richels, 2001; Tanaka et al., 2010) and will not be discussed further here. Several of the most relevant studies are listed in Table 6.

The second view addresses the limitations of the metric from the point of view of climate science and is concerned with the repercussions of these limitations on policies. The motivation for this study is based on this view. A summary of the main limitations, from the perspective of climate science and policy implications, is presented below.

The third view accepts GWP's limitations, as expressed by the first two views, given the difficulty of designing a better metric within the context of the complexity of the climate system. It focuses on the transparency of the formulation and the absence of a better alternative. It is the view adopted up until now in climate change policy contexts, and is the view this study purports to challenge.

The choice between metrics based on radiative forcing or temperature is irrevocably associated with a major trade-off, already discussed in Section 3.5: the increasing uncertainty in the estimation of the parameters as one moves along the climate change chain, in opposition to the increasing relevance of the parameters as proxies for climate change impact. Surface temperature change is a better proxy for damage or impact than integrated radiative forcing, yet it embodies the larger uncertainty of the climate sensitivity parameter (see section 4.4.5.1). On the other hand, radiative forcing is a quantitatively more reliable metric than temperature change. Although it is dependent on complex atmospheric chemistry, particularly CH_4 (Hayhoe et al., 2000), the uncertainty embedded in its definition is still smaller than that of surface temperature change.

One of the main limitations of GWP derives precisely from the difficulty in defining what impact a radiative forcing-based metric represents. The term 'warming potential' is misleading, for the relationship between the radiative forcing which results from a pulse emission and its warming potential is not a simple one (Smith and Wigley, 2000 a,b; Shine et al., 2005, Fuglestvedt, et al., 2005). Two gases with the same GWP will not necessarily have the same temperature impact, neither in magnitude nor in time, on the climate system. In other words, two different gases, one with a high specific radiative forcing parameter *A* and a short adjustment time α and the other with a low *A* and large α, may have similar GWPs (Shine, Fuglestvedt, et al., 2005). Equating GWP-equivalence with temperature equivalence can lead to false impact forecasts, although there are exceptions in idealized scenarios. From a GWP-based perspective, if CH_4 is considered to be 25 times as impacting as CO_2, further on along the climate change chain, such as when considering temperature change, this multiplier will not be the same. Critics who espouse O'Neill's (2003) first view could ask, for instance, if CH_4 carbon credits should be worth 25 times those for CO2. In other words, the impact proportions suggested by GWP cannot be attributed in such a straightforward manner to impacts at the end of the chain, nor to their costs for society.

Our main concern here is the other main limitation common to both GWP and GTP metrics, consisting of their time-invariance and the consequences of the choice of a fixed time-horizon. These metrics are therefore independent of the goal of policies. As pointed out by Shine et al. (2007), it is possible that the lack of long-term target in the Kyoto Protocol may have contributed to GWP's acceptance. There are two characteristics of emissions which are not taken into account by the use of a time-invariant or fixed metrics: the actual time period between the moment the emission occurs and the impact target year, and the target year itself. For GWP, the choice of time-horizon over which to integrate the radiative forcing is critical, particularly for short-life GHGs, as already mentioned, yet typically multi-gas studies and policies do not take this time-period and the target year into account, calculating the CO_2-equivalent based on the GWP with a fixed 100-year time-horizon (GWP-100), adopted by the Kyoto Protocol without any objective criteria.

This study is concerned mainly with the time-invariance limitation of emission metrics, so we present a review of studies proposing radiative forcing-based metrics which take the treatment of time into account.

Rosa and Schaeffer (1995) proposed a variant of the GWP metric which compares the instantaneous radiative forcing caused by varying emissions of CO_2 and CH_4 and addresses two limitations of the traditional GWP, the assumption of a unit pulse emission, and the indirect effects of the oxidation of CH_4 into CO_2. The authors show that Brazilian hydroelectric reservoirs produce less emissions over a long time-horizon than fossil-fueled power generation.

There has been a recent focus on the treatment of time in life-cycle analysis (LCA), where up until recently temporal issues were discussed mostly in the context of biofuels. The traditional approach to LCA illustrates the time-invariance limitation of GWP very well, for emissions from different processes as well as emissions over time are typically aggregated into one single emission pulse and GWP-100 is applied to these aggregates. This practice introduces temporal distortions, especially in the analysis of long processes, such as thermoelectric power-plants, residential buildings or land-use change, and whenever comparisons must be made between analyses which use different temporal boundaries. In the field of biofuels, O'Hare et al. (2009) defines a integrated radiative forcing, the fuel warming potential, to compare biofuels and fossil fuels. Kendall et al. (2009) proposes a time correction factor which accounts for the timing of GHGs emitted at the beginning of the biofuel cultivation. The British Standards Institution's guidelines for LCA of emissions of goods and services defines a time discount factor for long processes (BSI, 2013). Levasseur et al. (2010) introduces the concept of a dynamic characterization factors based on radiative forcing and applies it to a LCA analyzing the effect of substituting gasoline for corn-based ethanol, and show that the time-invariant LCA methodology underestimates the impact of land-use change emissions, compared to the dynamic LCA proposed by the authors.

Peters et al. (2011) calculate CO_2-equivalents for the 3 main GHGs and for 6 short-lived pollutants for GWP and GTP, with time-horizons 20, 50 and 100, in a transportation sector life-cycle analysis.

The dependence of the GWP metric on the interval over which the radiative forcing is integrated is particularly relevant for short-lived gases. If a gas decays rapidly compared to the decay time of the reference gas CO_2, as a time-horizon further away from the moment of emission is chosen, the numerator becomes a progressively smaller fraction of the denominator. After 14 years, approximately two-thirds of CH_4 molecules are no longer present in the atmosphere, yet two-thirds of CO_2 molecules are no longer present only after 120 years. For CH_4, the GWP for a time-horizon of 100 years is almost one third that for a time-horizon of 20 years, according to IPCC Fourth Assessment Report values. The choice of a long time-horizon, for instance, may lead to an underestimation of the weight of short-lived gases, in which case use of GWP could motivate policies which focus on reducing emissions of long-lived GHGs emitted by combustion of fossil-fuels and industrial processes, rather than short-lived gases. One relevant example of this limitation is in policies for the aviation sector, where multi-equivalency for short-lived pollutants[39] using GWP has been shown to lead to many uncertainties (Johnson et al., 1992; Wild et al, 2001; Stevenson et al., 2004; Svensson et al., 2004; Wit et al., 2005; Marais, 2008; Fuglestvedt et al., 2010). In a study conducted by Moura et al. (2012), the benefit of CCS is 90% if the plant is considered the boundary of the process, with only CO_2 emissions considered; with the inclusion of other criteria, such as the energy penalty, other GHGs, the choice of fixed or variable GWP, and the time-horizon, the benefit is reduced from 90% to 52%.

Finally, it should be mentioned that it is not the accuracy of the AGWP or AGTP which determines the usefulness of these metrics, but how accurately the ratio represents the relative impact of the GHG when compared to the reference gas.

The table below summarizes some of the main research conducted on GWP.

[39] Nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOC), black carbon (BC), and sulfur dioxide (SO2)

Table 6- GWP bibliographical review

Definition	(Shine, Fuglestvedt, et al., 2005)
Early discussions - Infinite TH and implications	(Fisher et al., 1990)
Definition	(Shine, Fuglestvedt, et al., 2005)
	(IPCC, 2007)
	(Fuglestvedt et al., 2010)
General criticism	(Rotmans and Den Elzen, 1992)
	(Skodvin and Fuglestvedt, 1997)
	(O'Neill, 2000)
	(Smith and Wigley, 2000a)
	(Manne and Richels, 2001)
	(Fuglestvedt et al., 2010)
	(Gian-Kasper et al., 2009)
Why it is accepted: Transparency of formulation, absence of acceptable alternative, acceptable also because Kyoto does not have specified long-term target (like constraining global mean RF or temperature increase) but just sets limits to CO_2-eq emissions	(Michaelis, 1992)
	(Skodvin and Fuglestvedt, 1997)
	(Manne and Richels, 2001)
	(Fuglestvedt et al., 2003)
	(van Vuuren et al., 2006)
	(Shine et al., 2007)
Limitation: Definition unclear about which aspect of climate change GWP is a proxy for.	(Fuglestvedt et al., 2000)
	(Smith and Wigley, 2000a)
	(Fuglestvedt et al., 2010)
Thermal inertia in the climate system is not accounted for by GWP	(Smith and Wigley, 2000a)
	(Forster et al., 2007)
	(Fuglestvedt et al., 2010)
Limitation: Nonlinearity of A and α	(Wuebbles et al., 1995)
	(Fuglestvedt et al., 2003)
	(Smith and Wigley, 2000a)
	(Smith and Wigley, 2000b)
Limitation: GWP-equivalence cannot be equated with temperature equivalence (there are exceptions in idealized cases)	(Fuglestvedt et al., 2010)
Limitation: GWP doesn't incorporate economic factors	(Eckhaus, 1992)
	(Schmalensee, 1993)
	(Reilly and Richards, 1993)
	(Manne and Richels, 2001)
	(Bradford, 2001)
	(Godal, 2003)
	(Kandlikar, 1995)
	(Fuglestvedt et al., 2010)
	(Tanaka et al., 2010)

(cont.)

Limitation:GWP does not account for indirect radiative forcing	(Rosa and Schaeffer, 1995)
	(IPCC, 2007)
Limitation: specific aspects concerning short-lived species	(Wild et al., 2001)
	(Collins et al., 2002))
	(Stevenson, 2004)
	(Berntsen et al., 2005)
	(Bond and Sun, 2005)
	(Shine et al., 2007)
	(Derwent et al., 2008)
	(Boucher and Reddy, 2008)
Assessment of GWP for short-lived components: uncertainty in chemical transport models precludes calculation of robust values for ozone as result of NOx emissions; same mass emission in different location can lead to different climate effects	(IPCC, 2001)
	(Berntsen et al., 2005)
	(Shine, Fuglestvedt, et al., 2005)
Assessment of GWP for long-lived components	(Forster et al., 2007)
Parameters conventionally chosen to represent present-day conditions, but can depend on background conditions	(Fuglestvedt et al., 2010)
Application to avionics - Arguments in favor of GWP for short-lived species in aviation:	
1. Continuity, specially for use in short-lived species because it is used in other areas of climate policy, but there is cost if applied incorrectly	(Godal, 2003)
	(O'Neill, 2003)
	(Aaheim et al., 2006)
	(Johansson et al., 2006)
2. Difficulty in defining GWP values for transport	(Fuglestvedt et al., 2010)
3.If GWP values are not available, other less suitable metrics might be used	(Fuglestvedt et al., 2010)
Application to avionics - general	(Wild et al., 2001)
	(Stevenson, 2004)
	(Svensson et al., 2004)
	(Wit et al., 2005)
	(Marais et al., 2008)

4.4.7. GTP limitations and advantages

Like GWP, the GTP metric is also a relatively simple metric. Estimating the impact of a non-CO_2 gas also requires nothing more than applying a multiplicative factor to emissions, and policymakers do not need to consider the parameters. Unlike GWP, the GTP metric relates the impact of the GHG to that of the reference gas according to a well-defined criterion, surface temperature change. Furthermore, while GWP represents a ratio of integrated radiative forcing over a period of time, GTP is an end-point metric, representing a ratio of temperature changes at an instantaneous moment in time.

But GTP's analytical formulations are nonetheless somewhat more complex and depend on more parameters than GWP. A study by Shine et al. (2007) comparing GTP with two other models (Manne and Richels, 2001; van Vuuren et al., 2006) indicates that the introduction of GTP into climate change policy would require constant parameter revisions, given the scientific progress on the evaluation of parameters. Even though it has the advantage of accounting for the target year of the policy, the need for such revisions could invalidate the use of GTP in broad long-term contexts. One specific limitation of the GTP formulation adopted in this study, that of Boucher and Reddy, as pointed out by Fuglestvedt (2010), consists in its disaggregation of the climate sensitivity into two parameters (c_1 and c_2 listed in Table 4), so that changing the climate sensitivity is not straightforward.

If even the values for the simple GWP metric have not been regularly updated, revising values for GTP would in all likelihood lead to even larger challenges. Ever since the UNFCCC adopted the GWP values of the IPCC Second Assessment Report (IPCC, 1995) for the Kyoto Protocol, estimates for the radiative forcing of GHGs have been continually updated in the literature. With improved modeling of atmospheric processes, more direct and indirect effects of emissions and new atmospheric background compositions have been taken into account, and GWP estimates have been shown to be increasing (Shindell et al. 2009, Reisinger et al., 2011). Metric values also change with each new IPCC report as the background atmospheric concentration changes. Still, GWP values used for emission inventories in policy contexts have remained the same since the IPCC Second Assessment Report.

Additionally, because there are several variants of the metric, which perform differently for different GHGs, as can be illustrated by the GTP_P and GTP_S variants by Shine et al., standardizing GTP in a legal context could therefore be even more challenging.

Unlike the case of the GWP metric, there have not been many studies applying the GTP metric to real emission scenarios.

Shine et al. (2007) calculate a time-dependent pulse-based GTP for two specific climate targets, temperature increase ceilings of 2^oC and 3^oC, for CH_4 and N_2O. They consider CO_2-equivalent pathways based on the A1F1 and B2 IPCC scenarios (IPCC, 2000) and calculate the time-dependent GTP-based weights for these GHGs which achieve the targets. They explore the dependence of the GTP metric on several modeling factors, such as the climate sensitivity parameter.

Berntsen and Fuglestvedt (2008) use the Boucher and Reddy model (Boucher and Reddy, 2008) to calculate temperature changes at different time-horizons due to emissions in the year 2000 and show how the mix of short and long-lived GHGs leads to very different relative results for the road and aviation sectors depending on the time-horizon chosen. The validity of studies for very short time-horizons have been contested based on the results of Berntsen and Fuglestvedt's study, as the magnitude of small changes are comparable to the natural variability of the climate system, yet their study illustrates well the importance of the difference between an integrated metric which weighs all forcings equally, such as GWP, and an end-point metric which weighs later radiative forcings more than earlier ones, for scenarios with a mix of short-lived and long-lived GHGs .

A study by Peters et al. (2011) stresses the importance of including short-lived pollutants such as NO_x, VOC, CO, BC and SO_2 in GHG mixes in the transport sector, and the limitations imposed by the use of GWP on such an analysis. The authors apply GWP and GTP, in their fixed variants, for three time-horizons, for the case of a specific European LCA transport sector database.

4.4.8. Summary of GWP and GTP comparison

The following table summarizes the main characteristics of the GWP and GTP metrics discussed in this chapter, and also compares them to exact indices, which are more precise indices derived directly from running energy balance models.

Table 7 – Comparison between assumptions and characteristics of GWP and GTP.

		GWP	**Shine GTP_P**	**Shine GTP_S**	**Boucher and Reddy**	**Exact Index (from EBM)**
Analytic form		Yes	Yes	Yes	Yes	No
Simplicity of analytical formulation		Very high	High	High	Medium	-
Acceptability in legal context		High	Low	Low	Low	Low
Input parameters	Specific radiative forcing A	Yes	Yes	Yes	Yes	Many
	Life-time α	Yes	Yes	Yes	Yes	
	Time-horizon TH	Yes	Yes	Yes	Yes	
	Climate sensitivity λ	No	Yes	Yes	Two parameters c_1 and c_2	
	System heat capacity C	No	Yes	Yes	Yes	
A, α constant assumed to be independent of gas etc		Yes	Yes	Yes		No

(cont.)

λ constant, assumed to be independent of mechanism causing RF	-	Yes	Yes		No
Thermal inertia is represented by ocean mixed layer with one constant C	-	Yes	Yes		No
Robustness to uncertainty	High	Medium. GTP is less sensitive to variation in λ than AGTP	Medium. GTP is less sensitive to variation in λ than AGTP	Medium. GTP is less sensitive to variation in λ than AGTP	Low
Relevance (unambiguous definition of impact)	Low	High	High	High	High
Allows inclusion of varying background atmospheric chemistry	No	No	No	-	Yes
Considers non-linearity between gas concentration and RF	No	No	No	-	Yes
Compared to EBM, performance for LLGHG	-	High	Medium for gases with wide variety of lifetimes	High	-
Compared to EBM, performance for SLGHG	-	Low (for GTP_P to agree with EBM within 10%, TH>80)	Medium	High	-
Dependence on TH	High	High	High	High	
End-point (accounts for policy target year) or integrated impact:	Integrated	End-point	End-point	End-point	Both
Performance relative to GWP	-	-	Similar for TH>100 (coincidental)	-	-

Source: Prepared by the author

Note: References: Shine, Fuglestvedt et al., 2005; Boucher and Ready, 2008

4.5. Calculation of emissions based on GWP and GTP

4.5.1. Fixed GWP and GTP

Emission inventories generally aggregate pulse emissions occurring at different moments of time into fixed periods of time, such as months or years. The summed emissions for each GHG *x* are then multiplied by the GHG's GWP or GTP factor for that time-horizon, resulting in emissions in CO_2-equivalent units for each GHG, as shown in Equations 30 and 31:

$$\boldsymbol{E_x^{CO_2eq}} = \left[\sum_{t=t_i}^{t=t_f} \boldsymbol{E_x(t)}\right] . \boldsymbol{GWP_x(TH)}$$

Equation 30

$$E_x^{CO_2eq} = \left[\sum_{t=t_i}^{t=t_f} E_x(t)\right] . GTP_x(TH)$$

Equation 31

where

t_i = start of emission period

t_f = end of emission period

TH = time-horizon

$E_x(t)$ = emission pulse of gas x at time t in mass units

E_x^{CO2eq} = total emission of gas x for emission period in CO_2-eq units

This aggregation, however, is a simplification which may lead to erroneous comparisons, for a larger unique pulse consisting of an aggregated mass of emissions does not produce the same climate impact as the equivalent mass disaggregated into many smaller pulses at different times. As already discussed, the time-invariance of fixed GWP is one of the main limitations of the metric.

Additionally, the choice of time-horizon determines the moment in time when the impact is measured by the metric. If the target year of interest for the analysis happens to coincide with the time-horizon of the metric used, the comparison might be more realistic. As an example, if the GWP-100 metric is applied to a power-plant's emissions in the year 2000, and the target year of interest is 2100, then the choice of time-horizon is adequate. Yet if the target year of interest is 2050, the application of the GWP-100 metric might result in distortions when comparing the real relative impacts of gases with different lifetimes, such as CO_2 and CH_4, the two main GHGs emitted by power plants during their life cycles.

4.5.2. Formulation of variable GWP and GTP

There have been a few studies which use the concept of time-dependent GWP and GTP. The most relevant studies have been in LCA, as exemplified by Levasseur's time-dependent AGWP (Levasseur et al. 2010). Another relevant study was conducted by

Shine et al. (2007) who define a time-dependent GTPP(t) which provides multi-equivalency weights for non-CO2 GHGs in the context of a pre-defined stabilization CO2-equivalent pathway.

In the time-dependent GWP and GTP formulations used in this study, the emission pulse for each moment in time is weighed by the metric value corresponding to the time lag between the year of the emission and the target year. In this manner, the climate impact of the pulses is discounted according to the distance from the target year.

The variable metrics applied in this study can be defined as follows[40]:

$$\boldsymbol{E_x^{CO_2eq}} = \sum_{t=t_i}^{t=t_f} [\boldsymbol{E_x(t).GWP_x(T-t)}]$$ **Equation 32**

$$\boldsymbol{E_x^{CO_2eq}} = \sum_{t=t_i}^{t=t_f} [\boldsymbol{E_x(t).GTP_x(T-t)}]$$ **Equation 33**

where

t_i = start of emission period

t_f = end of emission period

T = target year

$T - t = TH$= time-horizon

$E_x(t)$ = emission pulse of gas x at time t in mass units

E_x^{CO2eq} = total emission of gas x for emission period in CO_2-eq units

40 We do not consider target years before the end of the period of emissions. If the target year is one year beyond the end of the period, or coincides with the end of the period, the terms in Equation 33 which correspond to GWP (0) and GWP(1), or GTP(0) and GTP(1), respectively, should not be considered, as these metric values are not defined in the model used (Moura et al., 2012)

So far, we have discussed the subject of metrics from a qualitative and quantitative perspective. That discussion embodies the methodology used in this study. In the next chapter (Chapter 5), the data used in the study is presented. It is shown how the emission time-series due to fossil combustion are calculated from the Brazilian energy balance (BEN, 2011). Then, the sector emissions, based on the Second Inventory (MCT, 2010), are presented.

5. Energy Data, Emission Factors and Emissions Data

Three types of data are used in this study: energy, emission factors and emissions. The energy data for Scenario 1A, described in Table 8, was obtained from the Brazilian Energy Balance (BEN, 2011). IPCC emission factors were used to calculate emissions caused by energy consumption in Scenario 1A (IPCC, 2006). All other scenarios use emissions data published in the MCT's Second Communication (MCT, 2010).

Table 8 below describes the scenarios, indicating where the data used in each scenario is derived from, and the emission period covered. Scenario 1 considers the energy sector, including both calculated fuel combustion emissions (1A) and published fugitive emissions (1B). Scenario 2 considers all sectors of Brazil's economy. Since Scenario 2 includes an energy sector as well, there are two analysis of the energy sector (1A and 2A). The emissions time-series of Scenario 1A is more detailed and longer than the emissions of Scenario 2, and is considered the main energy data in this study. So why is the energy data in Scenario 2A, based on the Second Communication (MCT, 2010), not excluded from the study? There are two main reasons. First, for the sake of coherence and completeness. When analyzing the entire economy in Scenario 2, it makes sense to leave all sectors in. Second, the MCT energy data, although shorter and less detailed, is useful as a validation for the BEB based energy emissions calculated in this study.

Table 8 – Scenarios and source of GHG emissions data.

		Individual emissions for 3 GHGs (CO_2, CH_4 and N_2O)
Energy sector Scenario 1	**Fuel combustion** Scenario 1A (3 cases:all period, all sectors; 2010, all sectors; all period, charcoal sector) (25 sectors)	Modified BEB 1970-2010
	Fugitive Scenario 1B (4 sectors)	MCT II (updated) 1990-2010
Entire economy Scenario 2	**Energy** Scenario 2A	MCT II 1990-2005
	Fugitive Scenario 2B	
	Industrial processes Scenario 2C	
	Agriculture and livestock Scenario 2D	
	Land-use and forestry Scenario 2E	
	Waste treatment Scenario 2F	
	All-sector total Scenario 2G	

Notes:
MCT II data was updated recently. Only the updated energy sector data was available.

The structure of this chapter reflects the organization of the scenarios.

Section 5.1 discusses the energy data to be used in Scenario 1A and presents the original work done creating a modified BEB from where emissions can be calculated.

Section 5.2 discusses emissions data. First, in Section 5.2.1, there is a discussion about global emission databases. Following, in Sections 5.2.2, 5.2.3 and 5.2.4, emissions from BEB fuel combustion, MCT fugitive emissions and MCT entire-economy emissions, respectively, are presented.

This chapter presents individual GHG emissions. The calculation of CO_2-equivalents is presented in Chapter 6.

5.1. Energy Data (for Scenario 1A – BEB fuel combustion)

5.1.1. Background

There are two main reasons why we choose to apply metrics to emissions resulting from the energy sector.

The first reason, as already discussed in Section 2.2, is the growing contribution of energy emissions in the Brazilian emissions matrix, particularly due to the increased use of fossil-fuels.

The second reason why we choose to apply metrics to emissions based on an energy consumption series is on account of the better accuracy and consistency[41] of energy statistics, particularly when compared to land-use change and forestry data. Energy statistics in Brazil have been reported more reliably[42] and for a longer period of time than records of economic activity in land-use change and forestry sectors. Additionally, it should be noted that energy balances report consumption and therefore result in more accurate emissions than production-based reporting (Boitier, 2012). In the case of the charcoal sector, which is CH_4-intensive and therefore quite relevant for this study, the Brazilian Institute of Geography and Statistics (IBGE, 2013b) uses a production approach, while the BEB reports wood consumption[43].

Since the length of the emission series is also important in the study of temporal effects, an effort was made to calculate the most accurate and longest energy emission series. Not only does the BEB report the most accurate energy consumption data available for Brazil, but the data spans a 41-year period, 1970-2010 (BEN, 2011)[44], while the most recent MCT data covers a 21-year period 1990-2010 (MCT, 2012).

---

[41] IPCC guidelines good practice classifies inventory quality according to transparency, completeness, consistency, comparability and accuracy (IPCC, 2006).

[42] The Energy Research Company is responsible for reporting annual energy supply and consumption, conversion processes and foreign trade (EPE, 2011). When this study was conducted, the 2011 edition (for base year 2010) was the latest available edition of the Energy Balance. To date, a summary of the 2013 edition is available.

[43] Personal communication with Raymundo Aragão Neto in November 2012.

[44] When this study was started, the BEB report for emissions in 2011 was not yet available.

Also, the center of emission mass for the 1970-2010 period is close to the reference year 2000, as will be explained in Section 7.3. It occurs in 1990 for CH_4 and 1994 for N_2O, so application of the GWP-100 metric results in impacts that occur close enough to 2100.

A few studies estimate Brazilian energy emissions (de Freitas and Kaneko, 2011) , but do not provide sector and fuel emissions for the 1970-2010 period as explicitly and at the same level of disaggregation into fuels and sectors as the database created in this study. In Scenario 1A, emissions resulting from fuel combustion, both fossil and biomass, are calculated based on the energy statistics reported in the BEB. The resulting database of time series details the absolute emissions for the three GHGs, due to consumption of 24 fuels by 25 economic sectors for 41 years.

Table 9 below summarizes the characteristics, advantages and disadvantages of the energy and emissions data sources used in this study.

Table 9 – Characteristics and advantages/disadvantages of energy and emission data sources.

	BEB	Modified BEB	MCT II	MCT II updated
Emission scenario covered	Fuel combustion	Fuel combustion	Entire economy	Entire economy
Length of time-series	From 1970 onwards, yearly.	41 years (1970-2010)	16 years (1990-2005)	21 years (1990-2010)
Number of sectors and fuels	21 final consumption sectors, 10 transformation sectors	25 final consumption sectors, 24 fuels	25 final consumption sectors, 24 fuels 4 sectors for fugitive emissions 7 sectors for all economy	25 final consumption sectors, 24 fuels 4 sectors for fugitive emissions 7 sectors for all economy
Emission factors		Control possible	Standard IPCC	Standard IPCC
Methodology		Bottom-up from fuel combustion	Mixed top-down and bottom-up, not enough detail; problems with steel sector and coal imports	Mixed top-down and bottom-up, not enough detail, discontinuity in methodology of last 5 years (2006-2010)

5.1.2. Modified Brazilian Energy Balance methodology

The Brazilian Energy Balance (BEB) accounts for all energy produced, transformed and consumed in Brazil, including production, imports, exports, stock variations, non-utilized energy, reinjection, losses in distribution and storage, 10 transformation sectors and 21 final consumption sectors.

We first calculate a two-dimensional 41-year energy series for the 1970-2010 period, based on BEB sectorial and fuel data. This series takes into account fossil fuel and biomass used for combustion. It does not include fuels used as feedstock, which according to IPCC Guidelines (IPCC, 2006), are accounted for in the Industrial Processes and Product Use (IPPU) sector.

The time series are then used to estimate the 1970-2010 emission series for CO_2, CH_4 and N_2O using average IPCC emission factors for each fuel from the IPCC

Guidelines[45]. The resulting two-dimensional time-series gives us the emission of each fuel in each sector for every year. From this we can derive two relevant time-series: one gives us the total emission of each final consumption sector, after summing the emission contributions from the fuel distribution in that sector; the other gives us the total emissions due to the use of each fuel by summing emissions over all sectors.

In order to extract fuel combustion transactions from the original BEB, before using it to calculate emissions, modifications were made to the BEB. A concordance matrix of -1s, 0s and -1s is applied to the original BEB, creating a modified BEB.

In the modified BEB, transactions needed to account for the gross domestic supply were left out; also removed were transformation sectors which do not deliver energy for final consumption from combusted fuel (such as oil refineries, natural gas plants, gasification plants, coke producers, ethanol distilleries), losses in distribution and storage (fugitive emissions), and fuel used for non-energy purposes, such as natural gas used as feedstock in the petrochemical industry or metallurgical coal used in steel manufacturing. Fuel combusted in the transformation sectors for self-consumption is accounted for in the energy sector, the first final consumption sector of the BEB.

Emissions must be accounted for in the sector where they are generated (IPCC, 2006). Emissions can therefore be computed directly from fuel use in the final consumption sectors, but emissions from electricity use and charcoal use in the final consumption sectors must be transferred to the transformation sectors. First, the concordance matrix applied to the original BEB accounts for electricity and charcoal emissions where secondary energy is produced, rather than where it is consumed. For this purpose, four transformation sectors are added to the BEB 21 final energy consumption sectors: three electricity generating sectors (nuclear fuel cycle, public service and auto-generating power plants), and charcoal producers. Second, the electricity final consumption column of the original BEB is eliminated, because the final consumption of electricity is transferred to the electricity production transformation sectors.

The modified BEB therefore consists of the original 21 final consumption sectors, plus 3 electricity transformation sectors and a charcoal production sector, in a total of 25

[45] According to the IEA, even though the IPCC approved the 2006 Guidelines at the 25th session of the IPCC in April 2006, many countries are still using the 1996 IPCC guidelines, used in the Kyoto Protocol. By April 15, 2015, use of the 2006 Guidelines for reporting tables will be mandatory, based on Decision 15/CP.17 (IEA, 2012b)

sectors. The modified BEB energy sources are the same as the original 24. Energy sources which are not combustible fuels but produce electricity, such as hydraulic and nuclear energy, were left in the modified BEB, and are later assigned zero emission factors. These energy sources and sectors are listed in Tables 10 and 11, respectively.

Table 10 - Brazilian energy balance Primary and secondary energy sources.

Brazilian Energy Balance Primary Energy sources		GHGs emitted from combustion
1	Crude oil	CO_2, CH_4, N_2O
2	Natural gas	CO_2, CH_4, N_2O
3	Steam coal	CO_2, CH_4, N_2O
4	Metallurgical coal	CO_2, CH_4, N_2O
5	Uranium U3O8	None
6	Hydraulic energy	None
7	Firewood	CH_4, N_2O
8	Sugar-cane products(molasses, juice, bagasse)	CH_4, N_2O
9	Other primary sources (vegetable and industrial residues for steam and heat)	CH_4, N_2O
Brazilian Energy Balance Secondary energy sources		**GHGs emitted from combustion**
10	Diesel oil	CO_2, CH_4, N_2O
11	Fuel oil imported	CO_2, CH_4, N_2O
12	Gasoline	CO_2, CH_4, N_2O
13	Liquefied Petroleum Gases (LPG)	CO_2, CH_4, N_2O
14	Naptha	CO_2, CH_4, N_2O
15	Kerosene	CO_2, CH_4, N_2O
16	Gas coke	CO_2, CH_4, N_2O
17	Coal coke	CO_2, CH_4, N_2O
18	Uranium contained in UO2	None
19	Electricity	CO_2, CH_4, N_2O (indirectly)
20	Charcoal	CH_4, N_2O
21	Anhydrous and hydrated ethyl alcohol	CH_4, N_2O
22	Other secondary oil products(refinery gas, coke)	CO_2, CH_4, N_2O
23	Non-energy oil products (greases, lubricants, paraffin wax, asphalt, solvents)	None
24	Bitumen or tar (Produced in transformation of metallurgical coke into coke)	CO_2, CH_4, N_2O

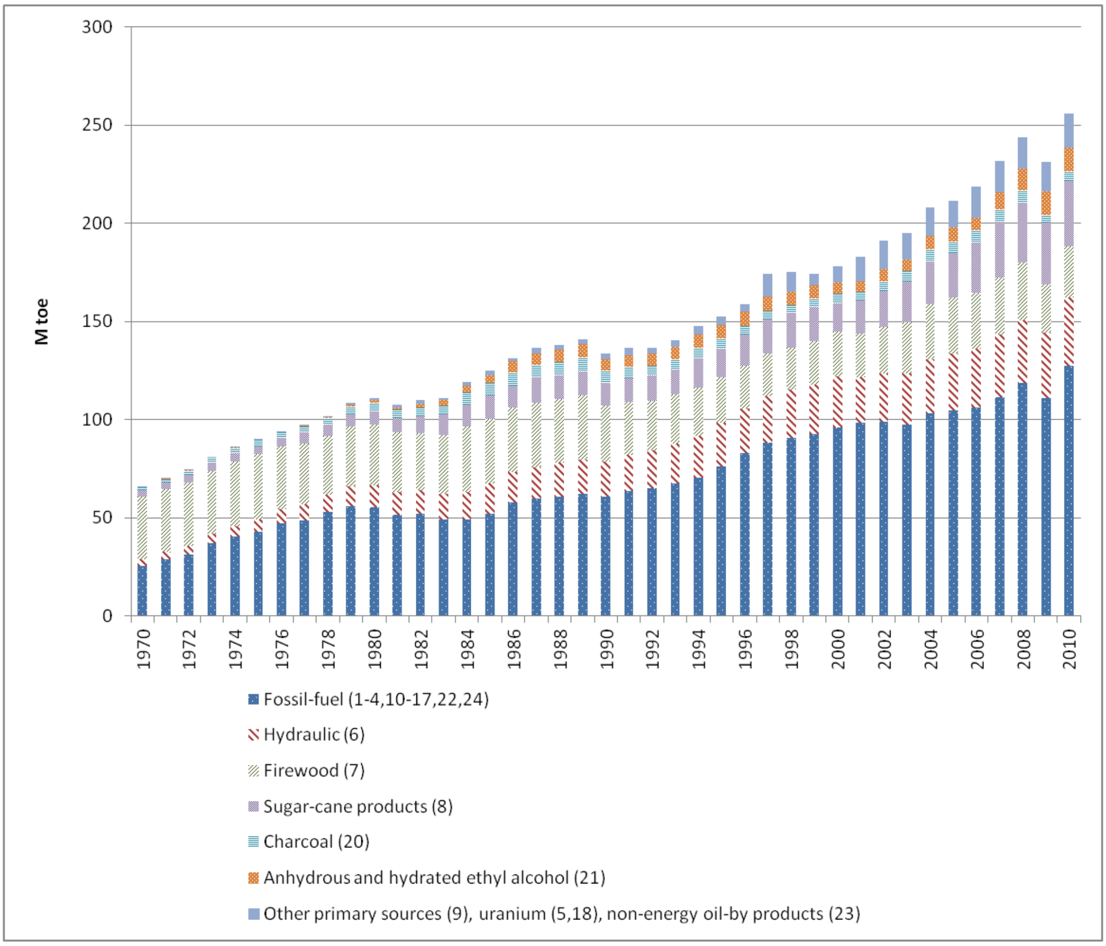
Table 11 - Brazilian energy balance transformation and final consumer sectors.

Brazilian Energy Balance Transformation sectors		
1	Nuclear fuel cycle	
2	Power plants: public service	
3	Power plants: self-generators	
4	Charcoal producers	
Brazilian Energy Balance Final consumer sectors		
5	Energy sectors (*1)	
6	Residential	
7	Commercial	
8	Public	
9	Agricultural/livestock	
10	Transportation	Road
11		Rail
12		Air
13		Waterways
14	Industry	Cement
15		Pig-iron and steel
16		Ferro-alloys
17		Mining and pelotization
18		Non-ferrous metals and other
19		Chemicals
20		Food and drink
21		Textiles
22		Pulp and paper
23		Ceramics
24		Other industrial sectors
25	Unidentified consumption	

Notes:
(*1) Self-consumption of energy transformation sectors.

Notes:
1) For clarity, fossil fuel consumption is aggregated in this figure (see Appendices F and G) . Primary fossil fuels are: oil (1), natural gas (2), steam (3) and metallurgical (4) coal. Secondary fossil-fuels are diesel (10), fuel oil (11), gasoline (12), LPG (13), naphtha (14), kerosene (15), gas coke (16), coal coke (17), bitumen (24) and other oil secondary (22) . See Table 10.
2) Energy sources which are considered to account for emissions are fossil fuels, firewood, sugar-cane products, charcoal and ethyl alcohol. Hydraulic, other primary sources, uranium and non-energy oil-by products are included here for the sake of depicting all energy sources.

Figure 5 shows the energy consumption of aggregated fossil fuels and renewable energy sources, for 1970-2010, as obtained from the modified BEB. These are the energy series used to calculate CO_2, CH_4 and N_2O emissions in Scenario 1A. The detailed energy consumption time-series are presented in the appendices, in table and graph format, for each of the 25 sectors (Appendices D and E) and for the 24 energy sources (Appendices F and G). There is no separate plot for electricity as an energy source, for the electricity consumption which contributes to emissions is distributed among the fuels used to produce electricity. These are the primary fuels natural gas, steam coal, sugar-cane products, wood and other primary sources (such as biomass and industrial residues), and the secondary fuels diesel, fuel oil, gas coke, other oil secondary fuels and bitumen.



Notes:
1) For clarity, fossil fuel consumption is aggregated in this figure (see Appendices F and G) . Primary fossil fuels are: oil (1), natural gas (2), steam (3) and metallurgical (4) coal. Secondary fossil-fuels are diesel (10), fuel oil (11), gasoline (12), LPG (13), naphtha (14), kerosene (15), gas coke (16), coal coke (17), bitumen (24) and other oil secondary (22) . See Table 10.
2) Energy sources which are considered to account for emissions are fossil fuels, firewood, sugar-cane products, charcoal and ethyl alcohol. Hydraulic, other primary sources, uranium and non-energy oil-by products are included here for the sake of depicting all energy sources.

Figure 5- Fossil and non-fossil (nuclear and renewable) energy consumption in 1970-2010 (10^6 toe).

Source: Prepared by the author based on BEB (BEN, 2011)

5.2. Emissions Data (Scenarios 1 and 2)

In this study, the accuracy of the time-series used to estimate the GWP and GTP metrics is of fundamental importance. For differences between metrics to be deemed relevant, they should be significant relative to the uncertainty in the emission estimates. Compounding this problem is the fact that we are analyzing a temperature-based metric, GTP, which accumulates more uncertainty than metrics derived from the beginning of the climate change chain, as explained in Section 3.5. Given any fixed emission series, no matter how inaccurate, inferences can indeed be made about the effect of the metric on the perception of the impact caused by those emissions. But in a case study, it only makes sense to be concerned about the effect of quantitative differences in the use of various metrics when the uncertainty in the emission series is comparatively lower than the difference in CO_2 equivalents resulting from the use of different metrics.

There is much uncertainty in emission inventories, particularly for non-CO_2 GHGs, yet estimating this uncertainty is a very difficult task. According to Prather et al. (2012), bottom-up inventory methods for industrially produced GHGs such as CO_2 from fossil fuel combustion are generally accurate to within 10%, while emission from CH_4 and N_2O can be even more uncertain, in the order of 25-50% for agriculture, forestry and land-use change. In a study of five industrialized countries (USA, UK, Norway, The Netherlands and Austria), uncertainty in national inventories was found to be ± 5 -20%, mainly due to subjective assessments of N_2O emissions relating to agricultural soils (Rypdal and Winiwarter, 2001). A study based on a new satellite-based model for monitoring deforestation, developed by the Brazilian National Institute for Space Research (Aguiar et al., 2012), shows that assigning emissions to forest clearance is not a straightforward task, for land clearance cannot be easily translated into emissions reduction. The authors state that emissions from deforestation and re-growth of secondary vegetation “are considered one of the most uncertain components of the global carbon cycle”. Their study shows that there is a lag between deforestation and emissions, so recent emission decreases do not reflect a recent decrease in deforestation. There was a 77% reduction in forest clearance in the Brazilian Amazon in the 2004 to 2011 period, from 27,772 km2 to 6,418 km^2, associated with an emission reduction of only 54%.

According to studies by Achard (2004) and Houghton (2008), revised rates of world land-use change for 1960-2000 in estimating world carbon emissions from deforestation resulted in significantly lower estimates when compared to a similar study performed in 2003 (Houghton, 2003). In the early 1980s, the emissions according to the older estimate amounted to approximately 2000 MtC, while the new estimate amounted to approximately 1500 MtC, a 20% difference.

As will be seen in the Chapter 7, in light of these estimates for emissions uncertainty, we will identify the differences between the metrics which are the most relevant.

In this section we present the emissions data used to calculate the GWP and GTP metrics, and compare them to 3 global databases, showing that in general the difference between emissions used in this study are within 10% of those reported by the global databases. It should be noted that a statistical analysis of the emission data obtained here was beyond the scope of this study.

5.2.1. Brazil Global Databases used for comparison

The energy emission time series calculated in this study are compared to emissions series listed for Brazil in the EDGAR, CDIAC and IEA global databases, to the Second Brazilian inventory (MCT, 2010) and to the updated Second Inventory.

5.2.1.1. Global databases: EDGAR

The Emission Database for Global Atmospheric Research (EDGAR) is a global emissions inventory database used for climate modeling, developed by the European Commission’s Joint Research Centre (EDGAR, 2013).

It covers the GHGs covers in the Kyoto Protocol (CO_2, CH_4, N_2O and fluorinated gases), the ozone precursor gases and acidifying gases (CO, NO_x, NMVOC, NH_3, SO_2) and primary particulates (PM10, BC, OC) as well as ozone depleting substances (CFCs etc). The database used in this study[46] covers 34 compounds and 53 IPCC source categories for 234 countries, for the 1970-2008 period.

The methodology used in EDGAR for calculation of emissions is a technology based emission factor approach. Emissions for each sector and year are calculated taking into account country-specific activity data, the mix of technologies for each sector, installed abatement measures and country-specific emission factors. Compared to the other global data bases used in this study (see Sections 5.2.1.2 and 5.2.1.3), EDGAR’s time-series is the most complete, for the data is based on several sources of information, such as the International Energy Agency (IEA), the US Department of Energy for coal, oil and gas consumption and production, country specific data and scientific literature.

In this study, the EDGAR emissions for CO_2, CH_4 and N_2O for 9 fuel combustion sectors were compared with the other global databases and with the MCT data for

[46] Most recent version v4.2, released in 2011.

Brazil. The 9 fuel combustion sectors correspond to source 1A in the IPCC source classification and are detailed in Table 12 below.

Table 12- IPCC Fuel Combustion Source Structure.

IPCC Fuel combustion source structure			EDGAR fuel combustion sector
1A Fuel combustion activities	1 Energy industries	1a Electricity and Heat Production	1
		1b Petroleum refining	2
		1c Manufacture of solid fuels and other energy industries	
	2 Manufacturing Industries and Construction	2a Iron and steel	3
		2b Non-ferrous metals	
		2c Chemicals	
		2d Pulp, Paper and Print	
		2e Food processing, Beverages and Tobacco	
		2f Non-metallic minerals	
		2g Transport equipment	
		2h Machinery	
		2i Mining (excluding fuels) and quarrying	
		2j Wood and wood products	
		2k Construction	
		2l Textile and leather	
		2m Non-specified industry	
	3 Transport	3a Civil aviation	4
		3b Road transportation	5
		3c Railways	6
		3d Domestic navigation	7
		3e Other transportation	8
	4 Other sectors	4a Commercial/Institutional	9
		4b Residential	
		4c Agriculture/Forestry/Fishing/Fish Farms	

Source: From IPCC, 2006, Vol. 2, Chapter 1, Fig 1.1.

5.2.1.2. Global databases: CDIAC

The Carbon Dioxide Information Analysis Center (CDIAC) is the main climate change information center of the U.S. Department of Energy. It provides global, regional and national estimates of carbon dioxide emissions from fossil-fuel consumption for 249 countries for the 1751 to 2009 period, as well as atmospheric concentrations of carbon dioxide and other gases, analyses of the carbon cycle and CO_2 responses to land-use, and other information (CDIAC, 2013).

The methodology adopted for historical emissions includes historical energy statistics of coal, peat and crude oil production (Andres et al., 1999). More recent data, since 1950, is derived from United Nations publications and the U.S. government.

Carbon emissions data for Brazil is available for the 1901-2008 period. Data is available for fossil-fuel emissions, disaggregated into gas, liquid and solid fuels, as well as for gas flaring and as for cement productions and bunker fuels (Boden et al., 1995).

In this study, the CDIAC emissions for CO_2 were compared with the other global databases and with the MCT data for Brazil. The emissions used were gas, liquid and solid fuels, transformed to CO_2 emissions, for the 1970-2008 period.

5.2.1.3. Global databases: IEA

The International Energy Agency publishes a large range of energy, economics and environmental statistics for 153 OECD and non-OECD countries. In this study, fuel combustion emissions are calculated from IEA energy data (IEA, 2012b) and IPCC emission factors (IPCC, 2006). The IEA provides data using two approaches: a sectoral approach, which uses data from individual fuel use in each sector, and a reference approach, which is a top-down methodology based on a country's energy supply and therefore also accounts for non-combusted fuel. In this study CO_2 emissions for the 1970-2008 period for both approaches are used for comparison with MCT data.

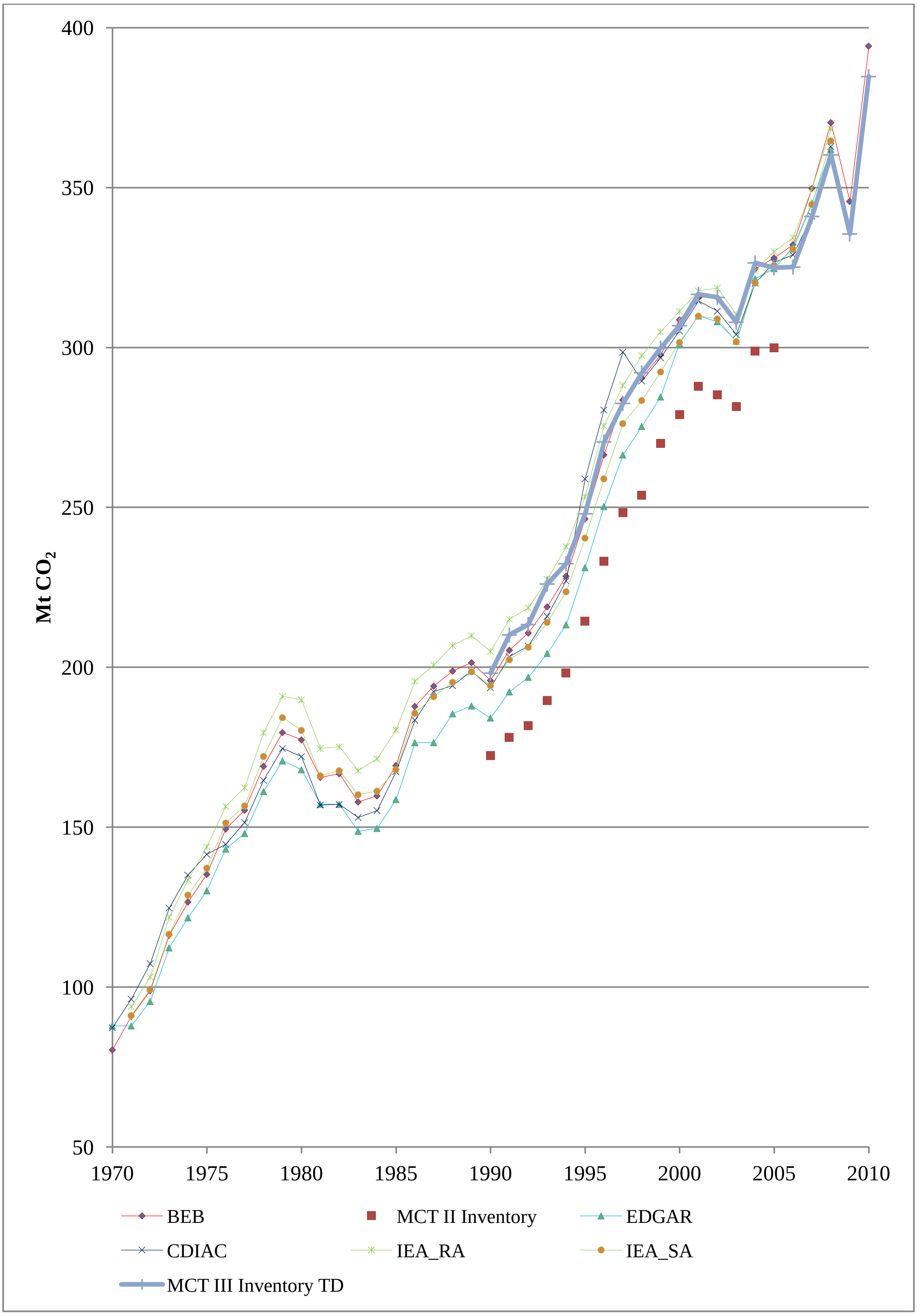
5.2.2. Fuel combustion based on BEB (Scenario 1A, 1970-2010)

A Tier 1 methodology, in which the amount of fuel combusted is multiplied by the default emission factor, is applied for all fuels. Emission factors adopted for the three GHGs are based on the IPCC guidelines default factors (IPCC, 2006). CO_2 emission factors used are derived from the carbon content of the fuel, as CO_2 emissions for fuel combustion are practically independent of the combustion process, and are therefore assumed to be the same for all sectors. The Tier 1 methodology therefore produces more accurate emission estimates for CO_2. Emission factors for CH_4 and N_2O, however, are dependent on technology, equipment specifications and operation conditions, so default sector-dependent values were adopted. IPCC lists lower and upper values for emission factors, but the values adopted here are the average default values. We also assume an oxidation factor of 1, as recommended by the IPCC .

The IPCC factors used correspond to 6 economic sectors: energy; industry and construction; residential and commercial; agricultural, fishing and forestry; and transportation. A concordance is made between the 6 IPCC sectors and the 25 BEB sectors, and the annual emissions for each of the 3 GHGs for each BEB sector are calculated from the fuel composition of each sector and emission factor for each fuel.

5.2.2.1. Fuel combustion: CO_2 emissions

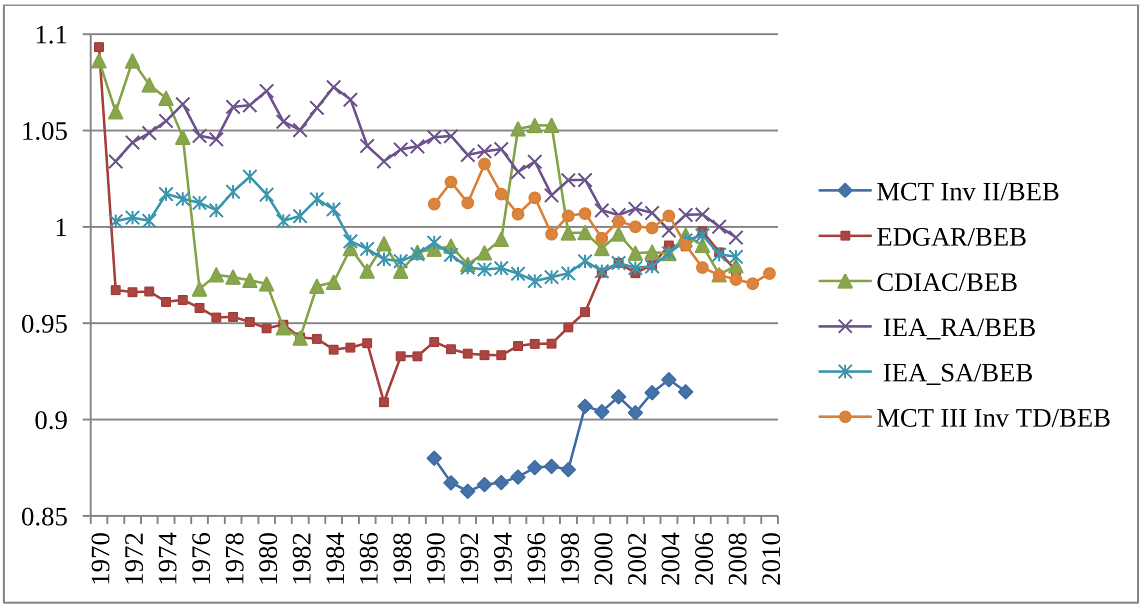
For non-fossil (biomass) combustion, CO_2 emissions are considered null for consumption of firewood, sugar-cane products, ethanol, charcoal and other primary sources (see Table 10). A country-specific emission factor was used for steam coal, assumed to be mined in Brazil. Figure 6 shows a plot of the BEB emission series for CO_2 calculated in this study, and contrasts the results with the four global databases and with the MCT Second Inventory.



Notes:
Emissions included for comparison are from MCT (Inventory II and updated Inventory II) , EDGAR, CDIAC and IEA Reference (IEA_RA) and Sectoral (IEA_SA) approaches. MCT III = updated MCT Second Inventory

Figure 6- CO_2 emissions from fuel combustion according to modified BEB.

As shown in Figure 7, where the plots in Figure 6 are normalized by the BEB series, the latter is within 10% of the emissions obtained from EDGAR and IEA Reference databases, and within approximately 5% for the CDIAC and IEA sectoral databases. Since the IEA sectoral database uses energy data based on individual fuel use in each sector, a similar methodology to the one used for calculating BEB emissions, the results are very close to the BEB results. The IEA Reference approach provides an upper bound to the sectoral approach, since it is a top-down approach that encompasses fuel which is not combusted, such as fugitive emissions. The IEA estimates that for most countries the gap between the two approaches is less than 5%, which is the case for Brazil[47]. The averages of the absolute differences over the period are 9.3 Mt CO_2 for EDGAR, 5.2 Mt CO_2 for CDIAC, and 6.5 and 3.4 Mt CO_2 for IEA reference and sectoral approaches, respectively. The MCT II Inventory emission series is within 15%, with an average difference of 29.5 Mt CO_2 over the period. The updated II Inventory is within 5% of the BEB emissions.



Notes: The vertical axis shows percentages normalized by BEB. MCT III = updated MCT Second Inventory

Figure 7 – CO_2 emissions for MCT, EDGAR, CDIAC and IEA normalized by BEB.

[47] In 2008, values are 368.3Mt for the reference approach and 364.6 for the sectoral approach, a difference on the order of 1%.

.

BEB emissions calculated here are larger than MCT II emissions. In 2005, BEB derived CO_2 emissions (327.99 Mt) are 28 Mt larger than the MCT bottom-up emissions (299.94 Mt), a difference which decreases to 18 Mt when compared to MCT top-bottom emissions [48] (309.98 Mt) (MCT, 2010). In the update of the Second Inventory, these differences are accounted for and the methodology used is revised[49].

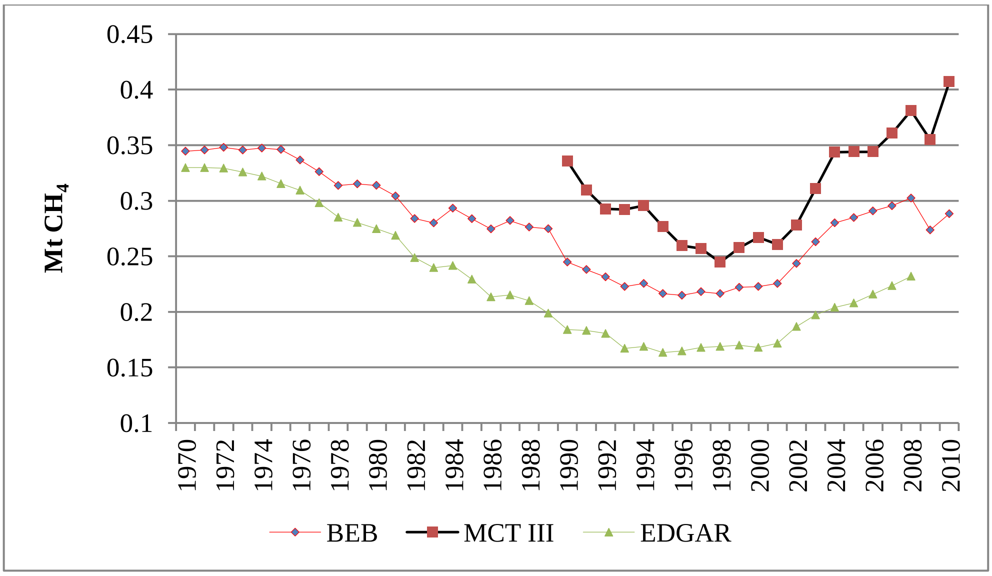
5.2.2.2. Fuel combustion: CH_4 and N_2O emissions

Because of the uncertainty due to dependence on technology and operating conditions, IPCC guidelines (IPCC, 2006) recommend the use of Tier 3 methodology for best results for non-CO_2 GHGs, whenever data is available. In this study, for the sake of consistency in the methodology, Tier 1 methodology is also applied to CH_4 and N_2O. The emission factors for these GHGs are for technologies without emission controls.

Figures 8 and 10 show the calculated BEB emission series for CH_4 and N_2O, respectively, and contrasts the results with plots of the two global databases and with the MCT II updated Inventory. CH_4 emissions in both MCT II inventories are the same for 1990-2005, so only the MCT updated inventory is plotted. Figures 9 and 11 show the plots normalized by the BEB emissions.

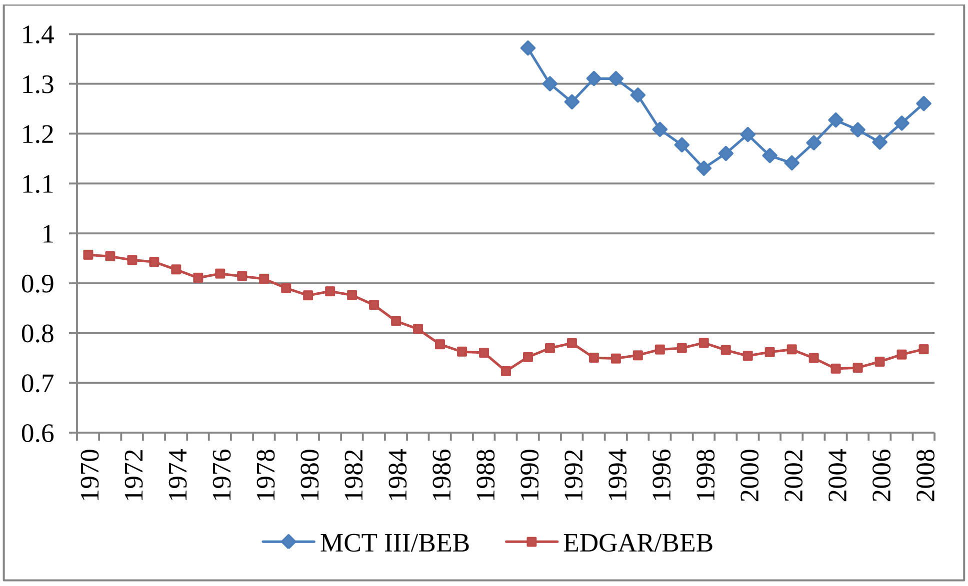
[48] Please refer to Volume 1, page 162, of Second Communication (MCT, 2010).

[49] According to the update, which had not been published yet when this study was conducted, imports of mineral coal were not accounted for correctly in the Second Inventory.



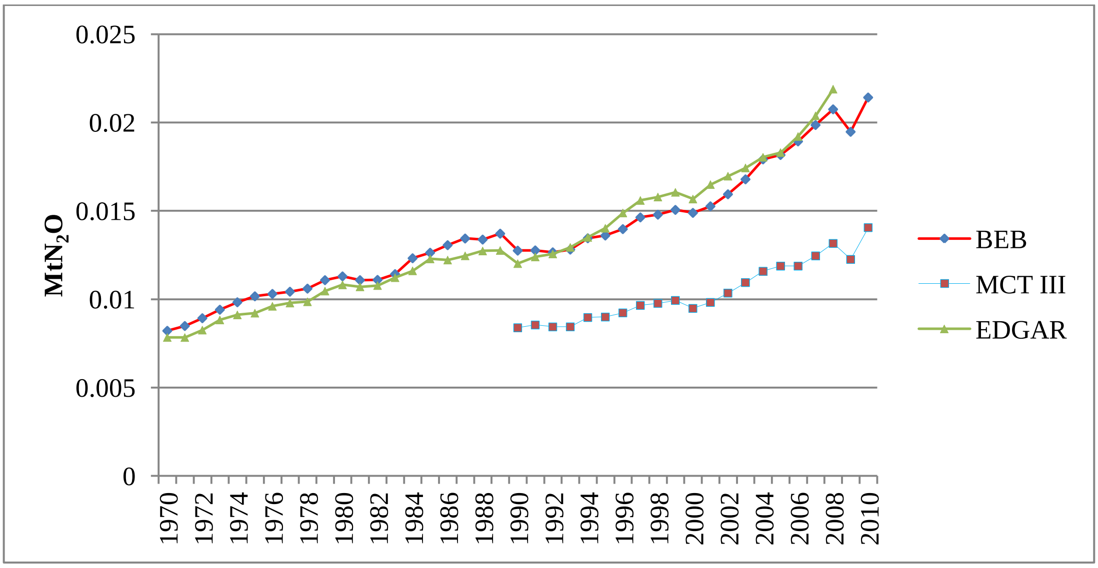
Notes:
Emissions included for comparison are from updated MCT and EDGAR.
MCT III = updated MCT Second Inventory
The decrease in emissions in the 1990-2004 period can be explained by the reduced emissions in wood combustion, relative both to charcoal producers and to residential use. In 1990, wood consumption by charcoal producers and residences was 12,780 and 7,960 ktoe, respectively, decreasing to 9,284 and 6,570 ktoe in 2000, and increasing again to 12,173 and 8,235 ktoe in 2005.

Figure 8 - CH_4 emissions from fuel combustion according to BEB.



Notes: The vertical axis shows percentages normalized by BEB

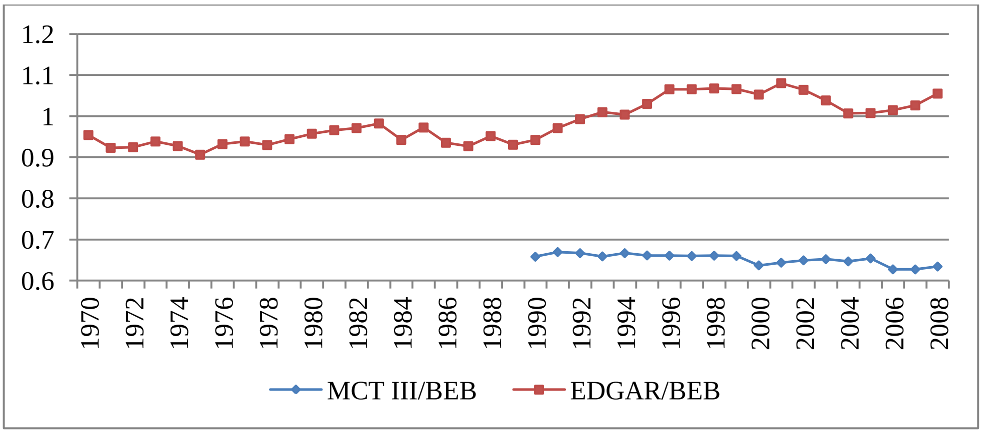
Figure 9- CH_4 emissions, normalized by BEB, for MCT and EDGAR.



Note:
Emissions included for comparison are from updated MCT and EDGAR.
MCT III = updated MCT Second Inventory

Figure 10 – N_2O fuel combustion emissions according to BEB.

.



Notes: The vertical axis shows percentages normalized by BEB. MCT III = updated MCT Second Inventory

Figure 11 – N_2O emissions, normalized by BEB, for updated MCT and EDGAR

CH_4 emissions estimated from the BEB are approximately 4% to 27% higher than the EDGAR emissions, and 13% to 38% lower than MCT emissions.

Since this study uses Tier 1 methodology and the MCT Second Inventory uses higher Tier methodology whenever possible, a difference between the estimates is expected.

The charcoal producers sector is responsible for the largest contribution to this difference.

In 2005, while the MCT Second Inventory estimates a CH_4 emission of 153 Gg for this sector, slightly less than half the total CH_4 emission (344 Gg), the estimate based on Tier 1 methodology with IPCC emission factors for firewood combustion results in 11 Gg, which is less than 5% of the total CH_4 emission (285 Gg) . In other words, the charcoal producer absolute emissions calculated from the BEB is an order of magnitude smaller than the emissions reported by the MCT. A likely explanation for this difference is our use of IPCC emission factors for firewood combustion. The IPCC default emission factor for firewood in the energy sector is 30 kg/TJ, while in the residential, agricultural and forestry sector the IPCC emission factor is an order of magnitude larger, 300 kg/TJ, thus accounting quite well for the difference. In Brazil, firewood combustion in the charcoal producer section is still relatively inefficient, with rates comparable to the efficiency in the residential, agricultural and forestry sectors[50]. Note also that there is a general reduction in the difference from 40% to 20% over 15 years, which could reflect a reduction in the firewood combustion emission factor during the period. In spite of this trend, since emission factors for this sector are highly uncertain, we decided to apply the IPCC default factor.

N_2O emissions estimated from the BEB emissions are comparable to EDGAR emissions (approximately 8% higher to 9% lower than EDGAR emissions), and 32% to 36% higher than MCT emissions. For this GHG, IPCC the emission factor used was 4 kg/TJ for all sectors, supposedly the same emission factor used by the MCT. No particular conclusion was reached to explain this difference, aside from fact that the MCT methodology uses a bottom-up approach wherever possible. N_2O emissions have been shown to have high uncertainties, and since biomass combustion accounts for about one third of N_2O emissions, this could account for the difference.

[50] Emission factors for wood combustion in the baseline scenarios of two recent Clean Development Mechanisms for Brazil were calculated in this study for comparison with the IPCC default factors. Assuming a net heating value of 4200 kcal/kg:

- *"Mitigation of Methane Emissions in the Charcoal Production of Plantar, Brazil"*, CDM #1051, 2007
  Emission factor = 789 kg CH_4 /TJ (assuming 0.29 t charcoal/t wood, 47.5 kg CH_4/t charcoal)
- *"Energia Verde Carbonization Project - Mitigation of Methane Emissions in the Charcoal Production of Grupo Queiroz Galvão, Maranhão, Brazil "*, CDM #4262 , 2010
  Emission factor =1214 kg CH_4/TJ (assuming 0.23 t charcoal/t wood, 89.0 kg CH_4/t charcoal)

5.2.3. Fugitive emissions based on updated MCT II (Scenario 1B, 1990-2010)

Fugitive emissions refer to escape without combustion. These emissions are not included in the BEB [51]. The graphs below show the MCT updated estimates disaggregated to show coal mining, E&P and refining fugitive emissions.

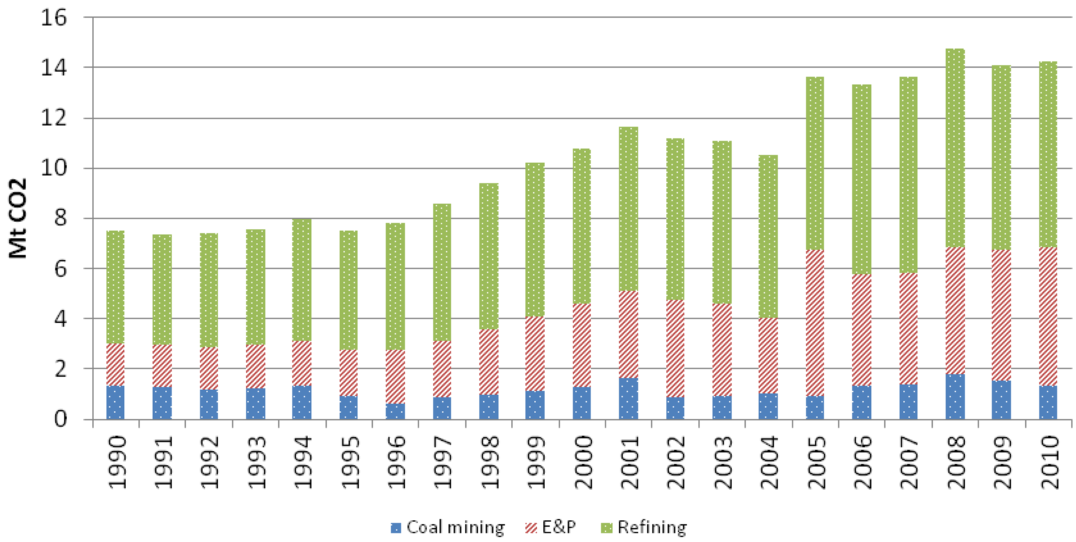


Figure 12 – Fugitive CO_2 emissions

[51] Personal communication with Raymundo Aragão Neto in November 2012.

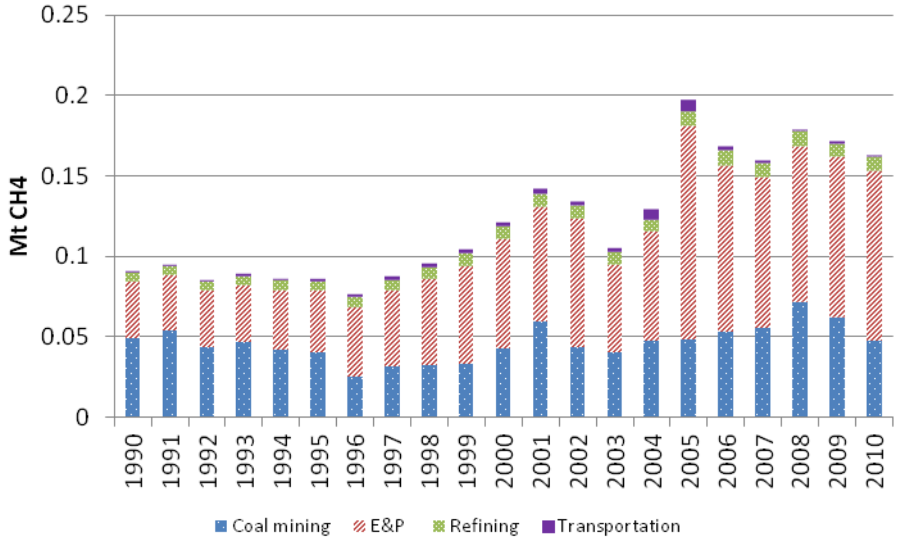


Figure 13 - Fugitive CH_4 emissions

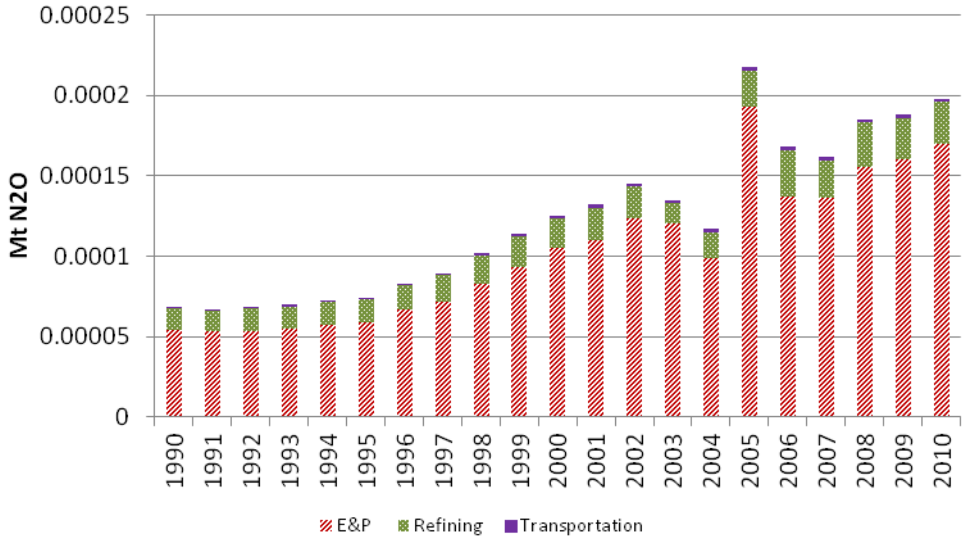


Figure 14- Fugitive N_2O emissions

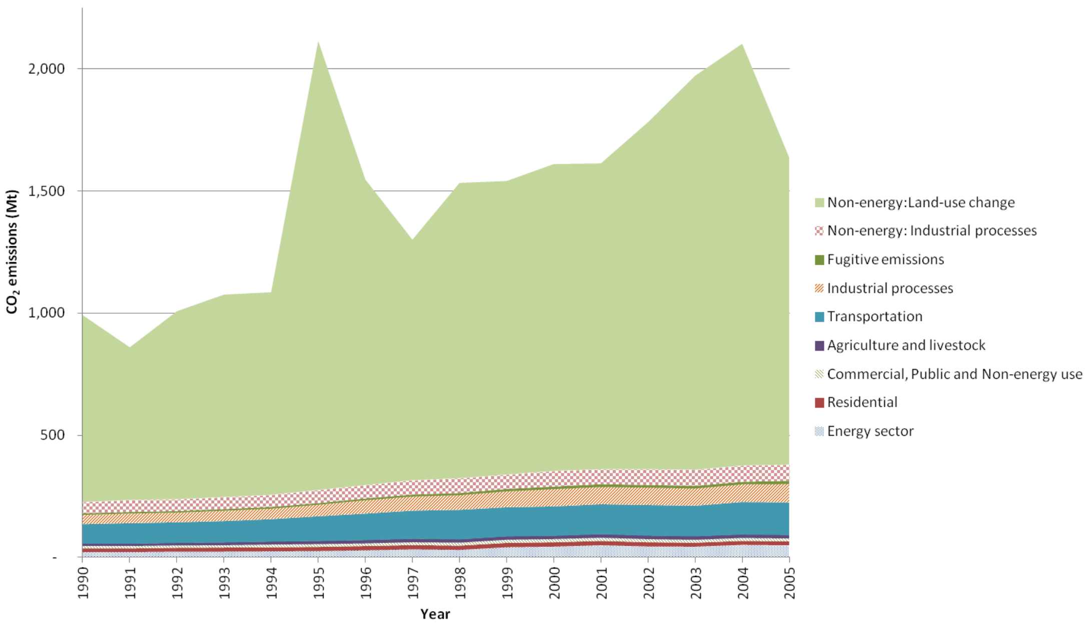
5.2.4. All-economy emissions based on MCT II (Scenario 2, 1990-2005)

Following IPCC guidelines, the MCT Second Inventory reports emissions according to six major sectors: energy, industrial processes and product use (IPPU), agriculture and livestock, land-use change and forestry, treatment of wastes, and other sectors[52]. A combination of top-down and bottom-up methodologies, and of Tier 1, 2 and 3

[52] The MCT reports emissions for a Use of Solvents and Other Products sector, but we have chosen not to consider these emissions in our calculations of CO2-equivalent, as they are very small relative to the other sectors.

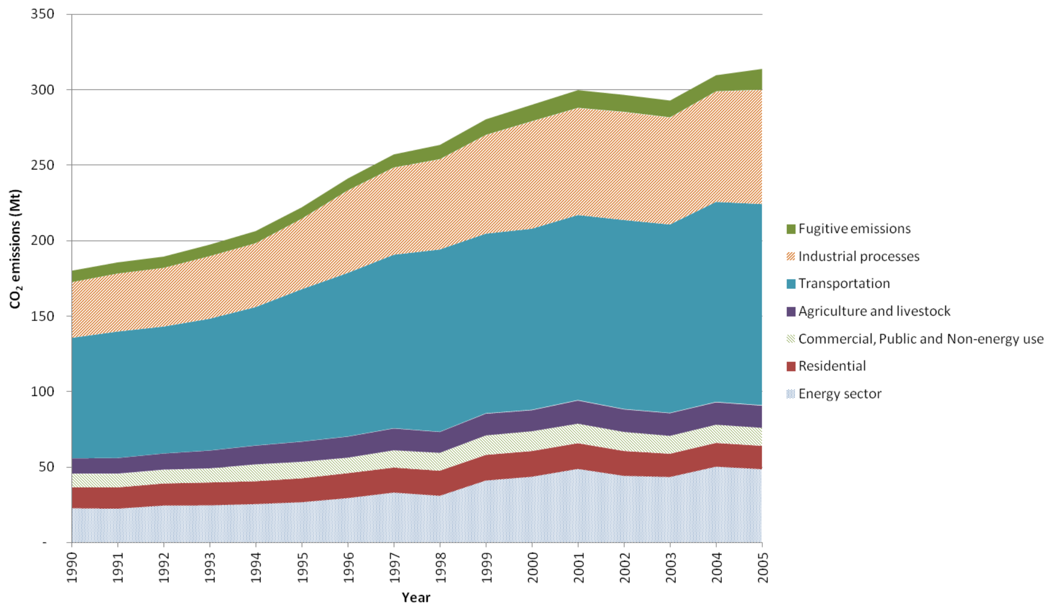
methodologies, is used by the MCT depending on the availability of data. Emissions are reported for CO_2, CH_4, N_2O, considered in this study, as well as five HFCs, CF_4, C2F6, SF_6, CO and NO_x and NMVOC, based on data from the Brazilian Energy Balance (BEB). In the case of CO_2 emissions, which depend primarily on the carbon content of the fuels, a top-bottom approach was considered acceptable in most cases. Emissions for the other gases are dependent on information concerning final use, such as the technology, equipment specifications and operation conditions, in which case a bottom-up methodology results in more accurate emissions, and was therefore adopted whenever data was available.

Figures 15, 17 and 18 show Brazil's total CO_2, CH_4 and N_2O emissions, respectively, resulting from economic activity for the 1990-2005 period. Figure 16 shows the energy sector CO_2 emissions, a detail of Figure 15. Emission increases from the beginning to the end of the period amounted to 65% for CO_2, 37% for CH_4 emissions and 45% for N_2O.



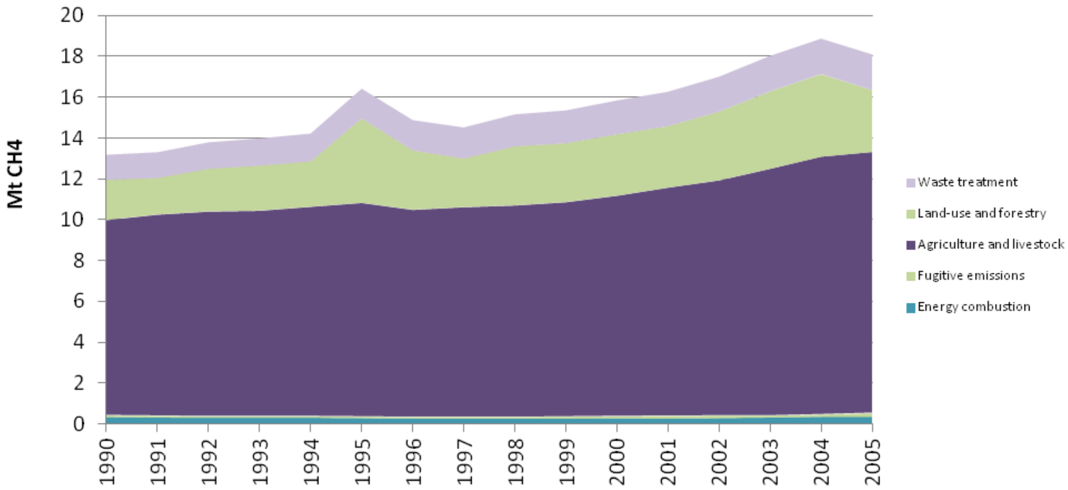
Notes:
In the legend, the first 2 sectors refer to non-energy emissions and the last 7 refer to energy emissions. The agriculture and livestock sector is considered to have zero CO_2 emissions, and the waste sector's emissions are insignificant (less than 0.11 Mt per year).

Figure 15 – CO2 emissions due to all economic sectors for 1990-2005
Source: MCT Second Inventory (MCT, 2010).



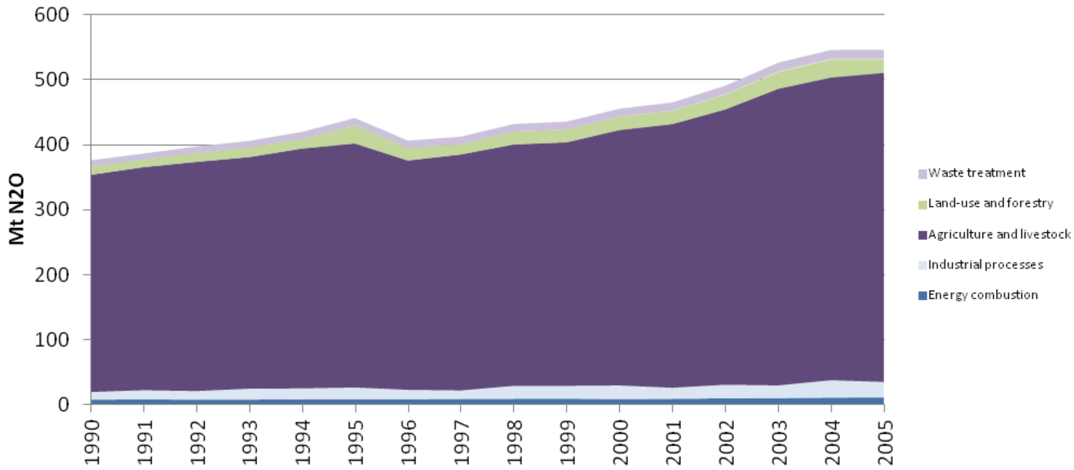
Notes: In the legend, the first 2 sectors refer to non-energy emissions and the last 7 refer to energy emissions. The agriculture and livestock sector is considered to have zero CO2 emissions, and the waste sector's emissions are insignificant (less than 0.11 Mt per year).

Figure 16 - Brazil's sectoral CO_2 emissions due to fuel combustion, according to the MCT 2006 Second Inventory, scaled-up detail from previous figure.



Notes: The combined total derived from energy combustion, fugitive emissions and industrial processes amounted to less than 3.3% of the total, with an average of 2.6% for the period. Emissions for industrial processes are insignificant and are not shown in the graph.

Figure 17– CH_4 emissions due to all economic sectors for 1990-2005
Source: MCT Second Inventory (MCT, 2010).



Notes: The combined total derived from fugitive emissions and industrial processes amounted to less than 7.6% of the total, with an average of 4.1% for the period. Emissions for fugitive emissions are insignificant and are not shown in the graph.

Figure 18 – N_2O emissions due to all economic sectors for 1990-2005
Source: MCT Second Inventory (MCT, 2010).

Summarizing, Chapters 3 and 4 discussed the subject of metrics from two different perspectives and Chapter 5 showed how the emissions data were developed. The following chapter (Chapter 6) presents the first stage of the study's results: the application of the metrics (the methodology of the study) to the emissions time-series of individual GHGs (the data), resulting in the CO_2-equivalent emissions for the various scenarios described in Chapter 5. The second stage of the results consist of an analysis of the quantitative results, presented in Chapter 7.

6. Results – CO_2 equivalents according to different metrics

This chapter presents the CO_2-equivalents calculated for each of the 11 scenarios (as described in Table 8). The information is presented in three formats: tables, graphs and summary diagrams. First, the results for each scenario are presented in a table and associated graph/chart, in sections 6.1 and 6.2. Second, in a pictorial summary, presented in section 6.3.

In the tables, the first three columns present the CO2-equivalent values calculated for each individual GHG time-series, summed over the entire period, using the 16 metrics: fixed GWP and GTP for time-horizons of 20, 35, 50 and 100 years, and variable GWP and GTP for impact years 2020, 2035, 2050 and 2100. The fourth column is the sum of the first three columns, and represents the total CO_2-equivalent for the GHGs.

The last four columns shows the percentage variation between the two metrics being compared, *relative to the variable metric*, for four comparisons : fixed GWP compared to variable GWP; fixed GTP compared to variable GTP; variable GWP compared to variable GTP; and fixed GWP compared to fixed GTP. The numerator of the percentage is the difference between the two metrics being compared (the first metric is always a fixed one and the second metric always a variable one), and the denominator is the second metric. For instance, if fixed GWP is being compared to variable GWP, the numerator is the fixed GWP minus the variable GWP, and the denominator is the variable GWP. In this manner, since the value of the fixed metric is often larger than that of the variable metric, the percentages are mostly positive, making the presentation of the comparisons simpler. A negative percentage shows to what extent the fixed variable is *smaller* than the variable metric. Shading in the tables is used to indicate the values used to calculate the percentages.

The figures show the same information in a graphical/chart format, highlighting the contribution of each GHG in the total metric value, the difference between the fixed and variable metrics, and the effect of the time-horizon on the metric values.

The analysis of these results is presented in Chapter 7.

6.1. Scenario 1A - Fuel combustion CO_2-equivalent emissions based on BEB (1970-2010)

Case 1: all period, all sectors

Table 13 - Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1A, Case 1. BEB 2070-3020 Energy: fuel combustion, all period, all sectors

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	9217.39	844.34	160.61	10222.34				
Var GWP 2020	9217.39	704.44	163.27	10085.09	1.4%			
Fix GTP-20	9217.39	686.97	167.61	10071.96				1.5%
Var GTP-2020	9217.39	461.81	171.13	9850.33		2.3%	2.4%	
Fix GWP-35	9217.39	624.31	168.44	10010.13				
Var GWP 2035	9217.39	538.26	169.35	9925.00	0.9%			
Fix GTP-35	9217.39	323.88	178.96	9720.22				3.0%
Var GTP-2035	9217.39	222.69	177.76	9617.84		1.1%	3.2%	
Fix GWP-50	9217.39	490.61	171.68	9879.68				
Var GWP 2050	9217.39	434.16	171.41	9822.95	0.6%			
Fix GTP-50	9217.39	146.47	179.82	9543.67				3.5%
Var GTP-2050	9217.39	109.18	175.75	9502.32		0.4%	3.4%	
Fix GWP-100	9217.39	291.42	166.59	9675.39				
Var GWP 2100	9217.39	271.03	164.79	9653.21	0.2%			
Fix GTP-100	9217.39	44.18	148.23	9409.80				2.8%
Var GTP-2100	9217.39	42.81	143.11	9403.31		0.1%	2.7%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

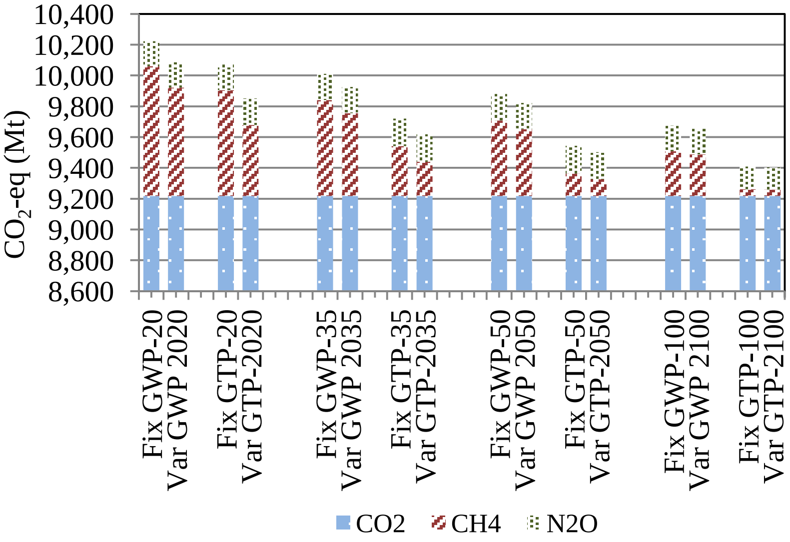


Figure 19- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1A, Case 1. BEB 2070-3020 Energy: fuel combustion, all period, all sectors

Case 2: all period, all sectors, one year (2010)

Table 14 - Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1A, Case 2. BEB 1970-2010 Energy: fuel combustion, one year 2010, all sectors

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	394.250	21.246	6.178	421.673				
Var GWP 2020	394.250	26.794	5.802	426.846	-1.2%			
Fix GTP-20	394.250	17.286	6.447	417.982				0.9%
Var GTP-2020	394.250	25.806	5.923	425.978		-1.9%	0.2%	
Fix GWP-35	394.250	15.709	6.479	416.438				
Var GWP 2035	394.250	19.074	6.303	419.627	-0.8%			
Fix GTP-35	394.250	8.150	6.883	409.283				1.7%
Var GTP-2035	394.250	13.658	6.638	414.545		-1.3%	1.2%	
Fix GWP-50	394.250	12.345	6.603	413.198				
Var GWP 2050	394.250	14.407	6.536	415.192	-0.5%			
Fix GTP-50	394.250	3.685	6.916	404.851				2.1%
Var GTP-2050	394.250	6.227	6.935	407.412		-0.6%	1.9%	
Fix GWP-100	394.250	7.333	6.407	407.990				
Var GWP 2100	394.250	7.949	6.488	408.687	-0.2%			
Fix GTP-100	394.250	1.112	5.701	401.063				1.7%
Var GTP-2100	394.250	1.190	5.989	401.429		-0.1%	1.8%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from

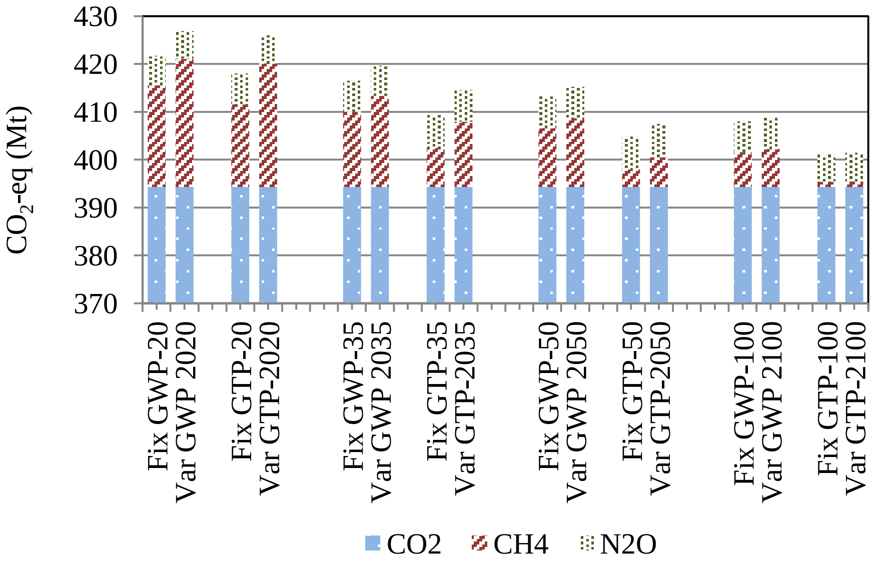


Figure 20 – Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1A, Case 2. BEB 1970-2010 Energy: fuel combustion, one year 2010, all sectors

Case 3: all period, one sector (charcoal)

Table 15 – Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1A, Case 3. BEB 1970-2010 Energy: fuel combustion all period, charcoal sector

Mt	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	36.262	18.916	55.177				
Var GWP 2020	31.673	19.329	51.002	8.2%			
Fix GTP-20	29.503	19.740	49.243				12.1%
Var GTP-2020	21.978	20.308	42.286		16.5%	20.6%	
Fix GWP-35	26.812	19.838	46.650				
Var GWP 2035	24.002	19.992	43.994	6.0%			
Fix GTP-35	13.910	21.076	34.986				33.3%
Var GTP-2035	10.520	20.993	31.513		11.0%	39.6%	
Fix GWP-50	21.070	20.219	41.290				
Var GWP 2050	19.232	20.203	39.435	4.7%			
Fix GTP-50	6.290	21.177	27.467				50.3%
Var GTP-2050	5.045	20.672	25.718		6.8%	53.3%	
Fix GWP-100	12.515	19.620	32.135				
Var GWP 2100	11.857	19.380	31.236	2.9%			
Fix GTP-100	1.897	17.457	19.355				66.0%
Var GTP-2100	1.853	16.759	18.612		4.0%	67.8%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

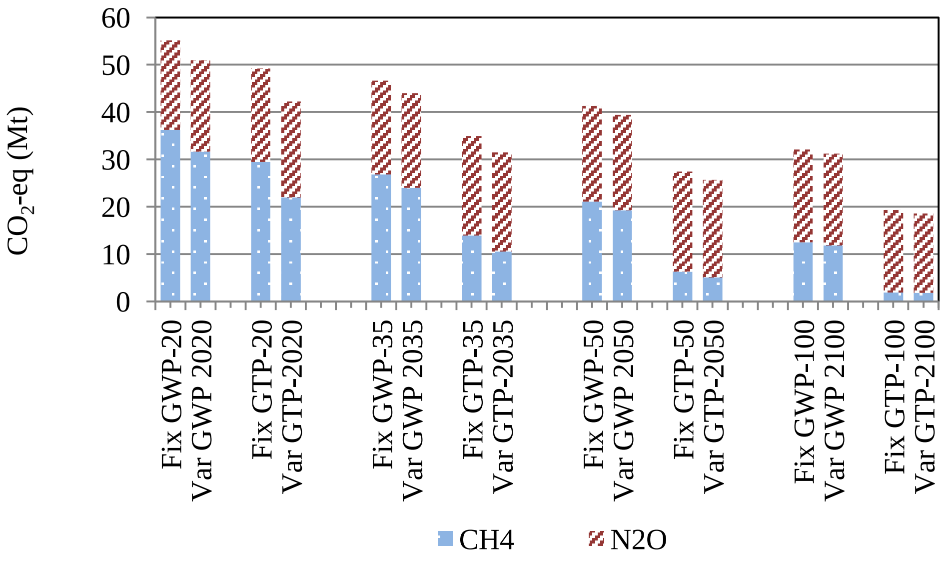


Figure 21 - Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1A, Case 3. BEB 1970-2010 Energy: fuel combustion all period, charcoal sector

Scenario 1B - Fugitive CO_2-equivalent emissions based on updated MCT II (1990-2010)

Table 16 - Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1B. MCT II 1990-2010 Energy: fugitive emissions, 4 sectors: coal mining, E&P, refining, transportation

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	221.75	189.63	0.75	412.13				
Var GWP 2020	221.75	199.04	0.74	421.52	-2.2%			
Fix GTP-20	221.75	154.29	0.78	376.82				9.4%
Var GTP-2020	221.75	168.39	0.76	390.90		-3.6%	7.8%	
Fix GWP-35	221.75	140.21	0.78	362.75				
Var GWP 2035	221.75	145.87	0.78	368.40	-1.5%			
Fix GTP-35	221.75	72.74	0.83	295.32				22.8%
Var GTP-2035	221.75	82.61	0.82	305.19		-3.2%	20.7%	
Fix GWP-50	221.75	110.19	0.80	332.74				
Var GWP 2050	221.75	113.59	0.80	336.14	-1.0%			
Fix GTP-50	221.75	32.90	0.84	255.48				30.2%
Var GTP-2050	221.75	37.61	0.84	260.20		-1.8%	29.2%	
Fix GWP-100	221.75	65.45	0.77	287.98				
Var GWP 2100	221.75	66.42	0.78	288.94	-0.3%			
Fix GTP-100	221.75	9.92	0.69	232.36				23.9%
Var GTP-2100	221.75	10.06	0.70	232.51		-0.1%	24.3%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

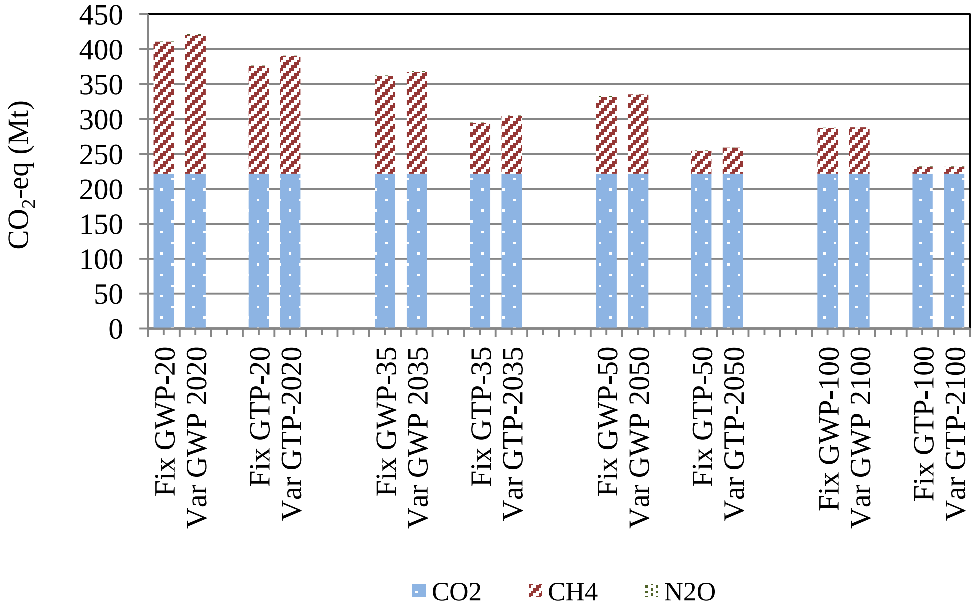


Figure 22 – Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 1B. Energy: fugitive emissions, 4 sectors: coal mining, E&P, refining, transportation

6.2. Scenario 2 - All-economy CO_2-equivalent emissions based on MCT II (1990-2005)

The emissions reported for the entire economy are for a shorter period of 16 years. The addition of CO_2-equivalent values presented for fuel combustion and fugitive emissions in sections, which are for 21 years, therefore result in larger emissions and are not directly comparable to these results.

Scenario 2A : Energy

Table 17- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2A. MCT II 1990-2005 Energy: fuel combustion

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	3872.77	340.91	44.56	4258.24				
Var GWP 2020	3872.77	325.75	44.86	4243.38	0.4%			
Fix GTP-20	3872.77	277.37	46.50	4196.64				1.5%
Var GTP-2020	3872.77	251.60	46.96	4171.33		0.6%	1.7%	
Fix GWP-35	3872.77	252.07	46.73	4171.57				
Var GWP 2035	3872.77	242.92	46.86	4162.55	0.2%			
Fix GTP-35	3872.77	130.77	49.65	4053.19				2.9%
Var GTP-2035	3872.77	118.27	49.70	4040.75		0.3%	3.0%	
Fix GWP-50	3872.77	198.09	47.63	4118.49				
Var GWP 2050	3872.77	192.22	47.65	4112.64	0.1%			
Fix GTP-50	3872.77	59.14	49.89	3981.80				3.4%
Var GTP-2050	3872.77	54.34	49.65	3976.76		0.1%	3.4%	
Fix GWP-100	3872.77	117.66	46.22	4036.65				
Var GWP 2100	3872.77	115.66	46.08	4034.52	0.1%			
Fix GTP-100	3872.77	17.84	41.12	3931.73				2.7%
Var GTP-2100	3872.77	17.68	40.71	3931.17		0.0%	2.6%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

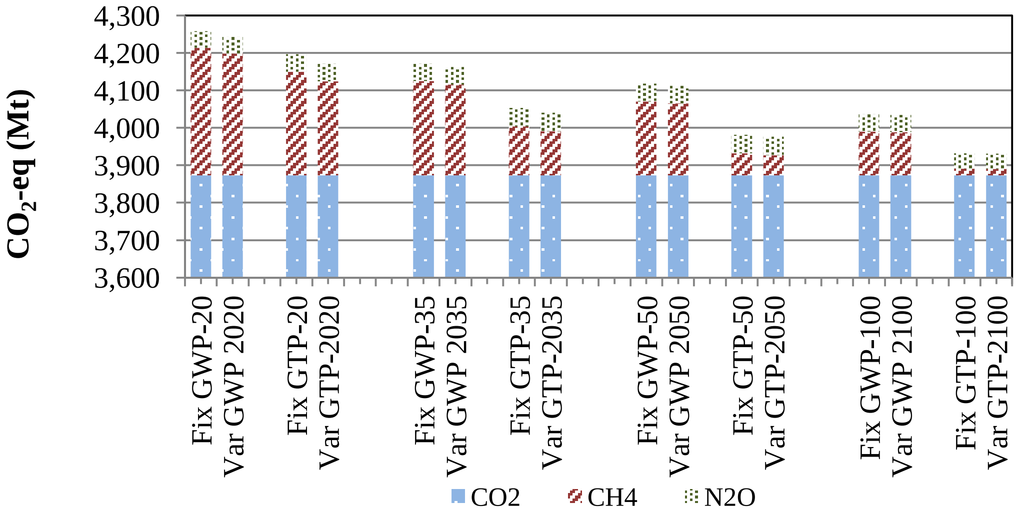


Figure 23 - Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2A. MCT II 1990-2005 Energy: fuel combustion

Scenario 2B: Fugitive

Table 18- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2B. MCT II 1990-2005 Energy: fugitive

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	151.26	127.57	0.49	279.31				
Var GWP 2020	151.26	124.31	0.49	276.05	1.2%			
Fix GTP-20	151.26	103.79	0.51	255.56				9.3%
Var GTP-2020	151.26	98.13	0.51	249.90		2.3%	10.5%	
Fix GWP-35	151.26	94.32	0.51	246.09				
Var GWP 2035	151.26	92.35	0.51	244.12	0.8%			
Fix GTP-35	151.26	48.93	0.54	200.73				22.6%
Var GTP-2035	151.26	46.40	0.54	198.21		1.3%	23.2%	
Fix GWP-50	151.26	74.12	0.52	225.90				
Var GWP 2050	151.26	72.84	0.52	224.62	0.6%			
Fix GTP-50	151.26	22.13	0.54	173.93				29.9%
Var GTP-2050	151.26	21.22	0.54	173.02		0.5%	29.8%	
Fix GWP-100	151.26	44.03	0.50	195.79				
Var GWP 2100	151.26	43.58	0.50	195.34	0.2%			
Fix GTP-100	151.26	6.67	0.45	158.38				23.6%
Var GTP-2100	151.26	6.64	0.44	158.35		0.0%	23.4%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

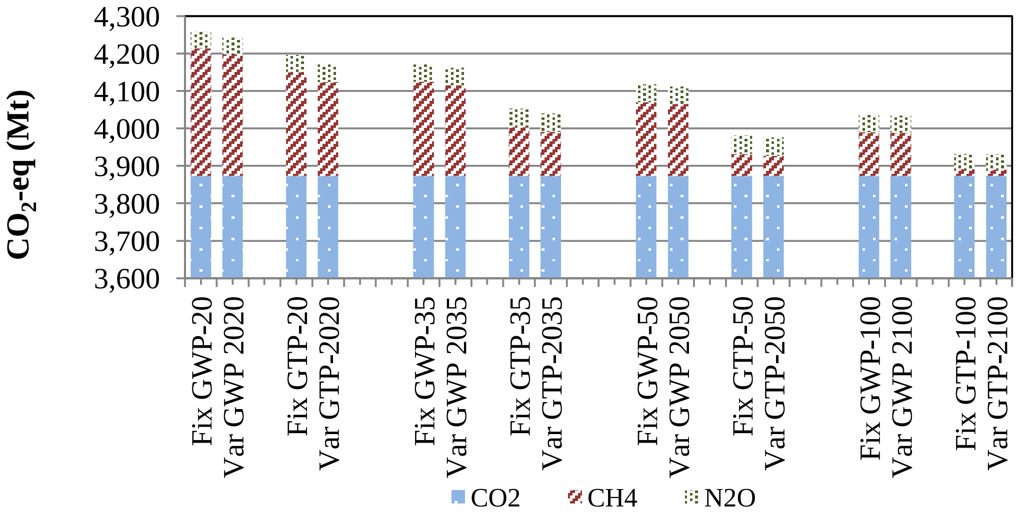


Figure 24- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2B. MCT II 1990-2005 Energy: fugitive

Scenario 2C: Industrial processes

Table 19- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2C.

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	904.61	8.48	79.13	992.21				
Var GWP 2020	904.61	8.24	79.52	992.37	0.0%			
Fix GTP-20	904.61	6.90	82.57	994.08				-0.2%
Var GTP-2020	904.61	6.49	83.19	994.29		0.0%	-0.2%	
Fix GWP-35	904.61	6.27	82.98	993.86				
Var GWP 2035	904.61	6.12	83.15	993.89	0.0%			
Fix GTP-35	904.61	3.25	88.16	996.03				-0.2%
Var GTP-2035	904.61	3.06	88.20	995.87		0.0%	-0.2%	
Fix GWP-50	904.61	4.93	84.58	994.12				
Var GWP 2050	904.61	4.83	84.59	994.04	0.0%			
Fix GTP-50	904.61	1.47	88.59	994.67				-0.1%
Var GTP-2050	904.61	1.40	88.22	994.23		0.0%	0.0%	
Fix GWP-100	904.61	2.93	82.07	989.61				
Var GWP 2100	904.61	2.89	81.88	989.39	0.0%			
Fix GTP-100	904.61	0.44	73.03	978.08				1.2%
Var GTP-2100	904.61	0.44	72.45	977.50		0.1%	1.2%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

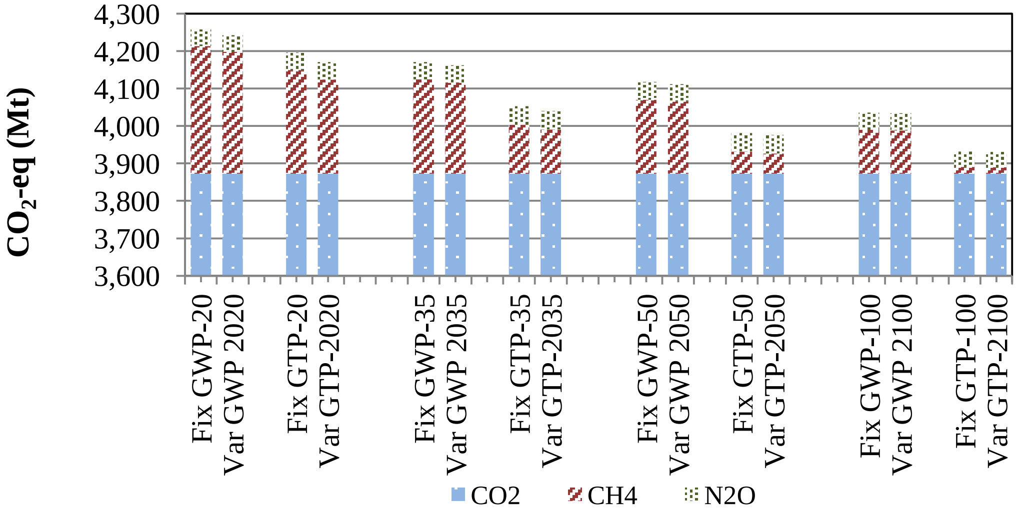


Figure 25 - Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2C. MCT II 1990-2005 Energy: Industrial processes

Scenario 2D: Agriculture and livestock

Table 20- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2D. MCT II 1990-2005 Agriculture and livestock

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	0	12691.15	1791.61	14482.76				
Var GWP 2020	0	12210.16	1803.56	14013.72	3.3%			
Fix GTP-20	0	10325.64	1869.67	12195.31				18.8%
Var GTP-2020	0	9505.28	1888.14	11393.42		7.0%	23.0%	
Fix GWP-35	0	9383.81	1878.95	11262.75				
Var GWP 2035	0	9093.53	1884.04	10977.57	2.6%			
Fix GTP-35	0	4868.17	1996.23	6864.40				64.1%
Var GTP-2035	0	4474.14	1998.28	6472.42		6.1%	69.6%	
Fix GWP-50	0	7374.30	1915.08	9289.38				
Var GWP 2050	0	7187.84	1915.67	9103.50	2.0%			
Fix GTP-50	0	2201.49	2005.81	4207.30				120.8%
Var GTP-2050	0	2051.40	1996.07	4047.47		3.9%	124.9%	
Fix GWP-100	0	4380.21	1858.30	6238.52				
Var GWP 2100	0	4316.31	1852.90	6169.21	1.1%			
Fix GTP-100	0	664.05	1653.49	2317.54				169.2%
Var GTP-2100	0	659.23	1636.96	2296.19		0.9%	168.7%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

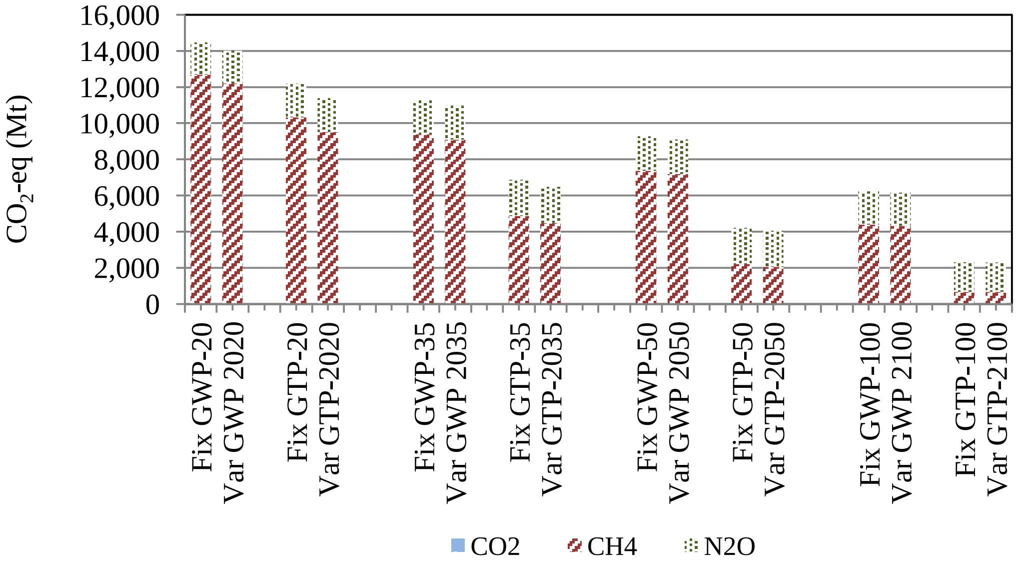


Figure 26- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2D. MCT II 1990-2005 Agriculture and livestock

Scenario 2E: Land-use and forestry

Table 21- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2E. MCT II 1990-2005 Land-use and forestry

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	18860.36	3393.30	91.35	22345.02				
Var GWP 2020	18860.36	3293.23	91.85	22245.44	0.4%			
Fix GTP-20	18860.36	2760.82	95.33	21716.52				2.9%
Var GTP-2020	18860.36	2588.94	96.11	21545.41		0.8%	3.2%	
Fix GWP-35	18860.36	2509.00	95.81	21465.17				
Var GWP 2035	18860.36	2448.56	96.02	21404.94	0.3%			
Fix GTP-35	18860.36	1301.63	101.79	20263.78				5.9%
Var GTP-2035	18860.36	1220.96	101.86	20183.18		0.4%	6.1%	
Fix GWP-50	18860.36	1971.71	97.65	20929.72				
Var GWP 2050	18860.36	1932.74	97.67	20890.78	0.2%			
Fix GTP-50	18860.36	588.62	102.28	19551.26				7.1%
Var GTP-2050	18860.36	558.47	101.85	19520.69		0.2%	7.0%	
Fix GWP-100	18860.36	1171.16	94.75	20126.28				
Var GWP 2100	18860.36	1157.69	94.52	20112.57	0.1%			
Fix GTP-100	18860.36	177.55	84.31	19122.23				5.3%
Var GTP-2100	18860.36	176.57	83.61	19120.55		0.0%	5.2%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

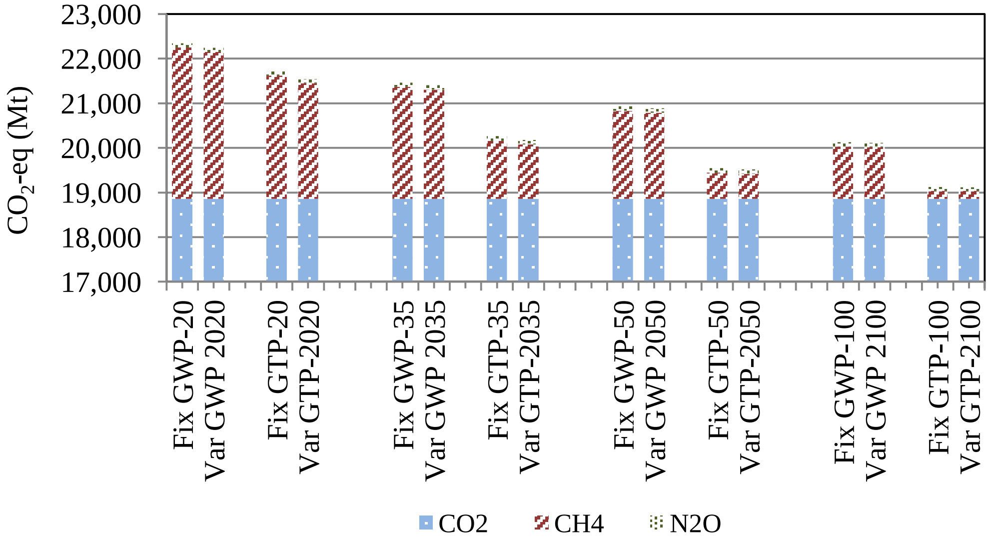


Figure 27- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2E. MCT II 1990-2005 Land-use and forestry

Scenario 2F: Waste treatment

Table 22- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2F. MCT II Waste treatment 1990-2005

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	1.19	1797.78	53.46	1852.43				
Var GWP 2020	1.19	1734.59	53.80	1789.58	3.5%			
Fix GTP-20	1.19	1462.69	55.79	1519.67				21.9%
Var GTP-2020	1.19	1354.80	56.31	1412.30		7.6%	26.7%	
Fix GWP-35	1.19	1329.27	56.07	1386.53				
Var GWP 2035	1.19	1291.14	56.21	1348.54	2.8%			
Fix GTP-35	1.19	689.60	59.57	750.37				84.8%
Var GTP-2035	1.19	637.94	59.62	698.76		7.4%	93.0%	
Fix GWP-50	1.19	1044.61	57.15	1102.95				
Var GWP 2050	1.19	1020.11	57.16	1078.46	2.3%			
Fix GTP-50	1.19	311.85	59.85	372.90				195.8%
Var GTP-2050	1.19	292.22	59.58	353.00		5.6%	205.5%	
Fix GWP-100	1.19	620.48	55.45	677.13				
Var GWP 2100	1.19	612.07	55.30	668.57	1.3%			
Fix GTP-100	1.19	94.07	49.34	144.60				368.3%
Var GTP-2100	1.19	93.44	48.88	143.51		0.8%	365.9%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

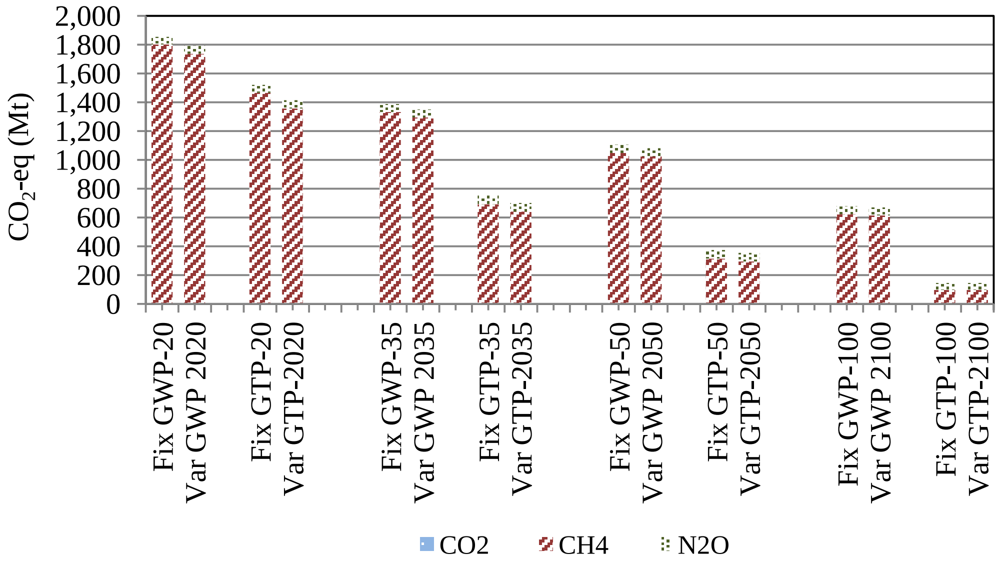


Figure 28- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2F. MCT II Waste treatment 1990-2005

Scenario 2G: All-sector total

Table 23 – Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2G. MCT II - All sectors 1990-2005

Mt	CO_2	CO_2-eq (CH_4)	CO_2-eq (N_2O)	CO_2-eq (Total)	Fixed vs. variable GWP	Fixed vs. variable GTP	Variable GWP vs. variable GTP	Fixed GWP vs. fixed GTP
Fix GWP-20	23,790.20	18,359.18	2,060.60	44,209.98				
Var GWP 2020	23,790.20	17,696.28	2,074.07	43,560.55	1.5%			
Fix GTP-20	23,790.20	14,937.20	2,150.38	40,877.79				8.2%
Var GTP-2020	23,790.20	13,805.23	2,171.22	39,766.65		2.8%	9.5%	
Fix GWP-35	23,790.20	13,574.73	2,161.05	39,525.98				
Var GWP 2035	23,790.20	13,174.62	2,166.79	39,131.61	1.0%			
Fix GTP-35	23,790.20	7,042.36	2,295.94	33,128.49				19.3%
Var GTP-2035	23,790.20	6,500.78	2,298.21	32,589.19		1.7%	20.1%	
Fix GWP-50	23,790.20	10,667.76	2,202.60	36,660.56				
Var GWP 2050	23,790.20	10,410.58	2,203.26	36,404.04	0.7%			
Fix GTP-50	23,790.20	3,184.70	2,306.96	29,281.86				25.2%
Var GTP-2050	23,790.20	2,979.06	2,295.91	29,065.17		0.7%	25.2%	
Fix GWP-100	23,790.20	6,336.47	2,137.30	32,263.98				
Var GWP 2100	23,790.20	6,248.20	2,131.19	32,169.59	0.3%			
Fix GTP-100	23,790.20	960.62	1,901.74	26,652.56				21.1%
Var GTP-2100	23,790.20	954.01	1,883.06	26,627.26		0.1%	20.8%	

Notes: The numerator of the percentage is the difference between the two metrics being compared (first metric minus second metric), and the denominator is the second metric. The shaded cells indicate the lines the values used to calculate the percentage are drawn from.

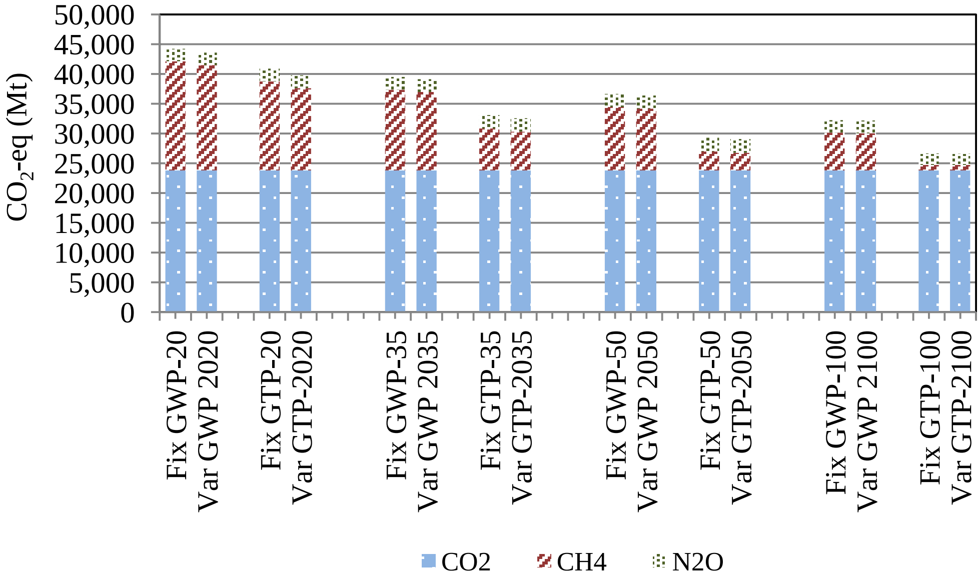


Figure 29- Comparison of CO_2-equivalents for fixed and variable GWP and GTP for Scenario 2G. MCT II - All sectors 1990-2005

6.3. Summary of results

This section shows the same results, as listed in Table 13 through Table 23 (and associated figures) of the first 3 sections of this chapter, in a diagram format.

In each element of the figures there are 4 ellipses. The elements in the first column of figures, starting on the left-hand-side of the page, refers to the time-horizon 2020, the second to 2035, the third to 2050 and ellipses in the last column refer to 2100 (on the far right of the page). Each line of figures refers to an emission scenario.

In each element of 4 ellipses:

- The upper ellipse shows the percentage difference when comparing emissions for the fixed and variable versions of GWP:

  (Fix GWP – Var GWP) / Var GWP

- The bottom ellipse shows the percentage difference when comparing the fixed and variable versions of GTP:

  (Fix GTP – Var GTP) / Var GTP

- The right-hand ellipse shows the percentage difference when comparing the variable versions of GWP and GTP:

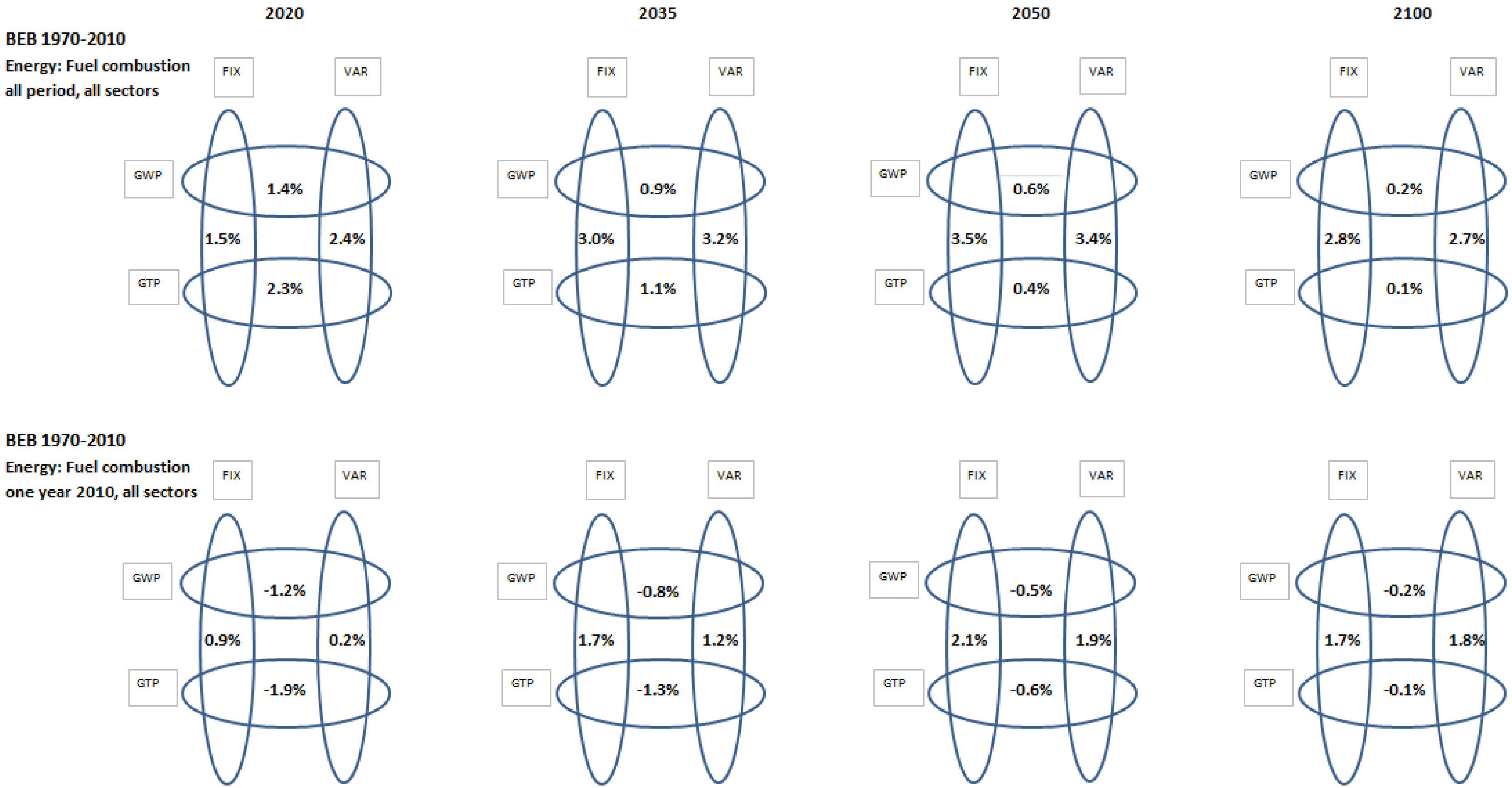
  (Var GWP – Var GTP) / Var GTP

- The left-hand ellipse shows the percentage difference when comparing the fixed versions of GWP and GTP:

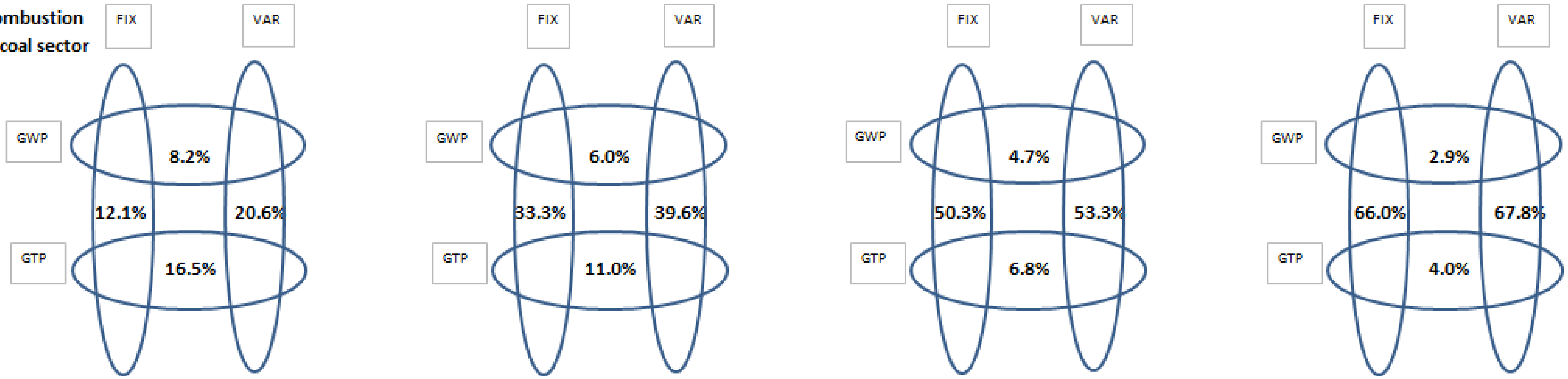
  (Fix GWP – Fix GTP) / Fix GTP

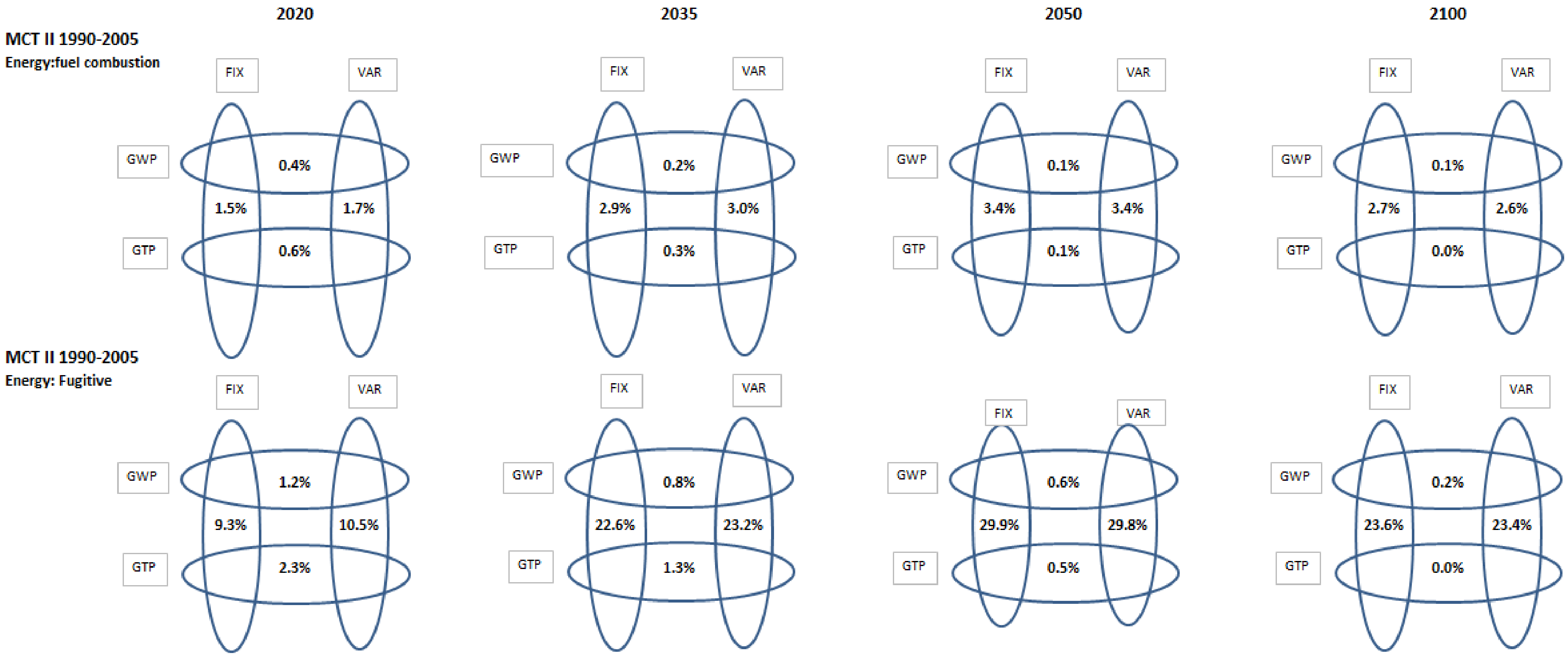
Example: For the scenario BEB 1970-2010, Energy: fuel combustion for all periods and all sectors, the upper ellipse shows (corresponding to value in Table 13):

(10,2222.34 – 10,0085.09) / 10,0085.09 = 1.4%

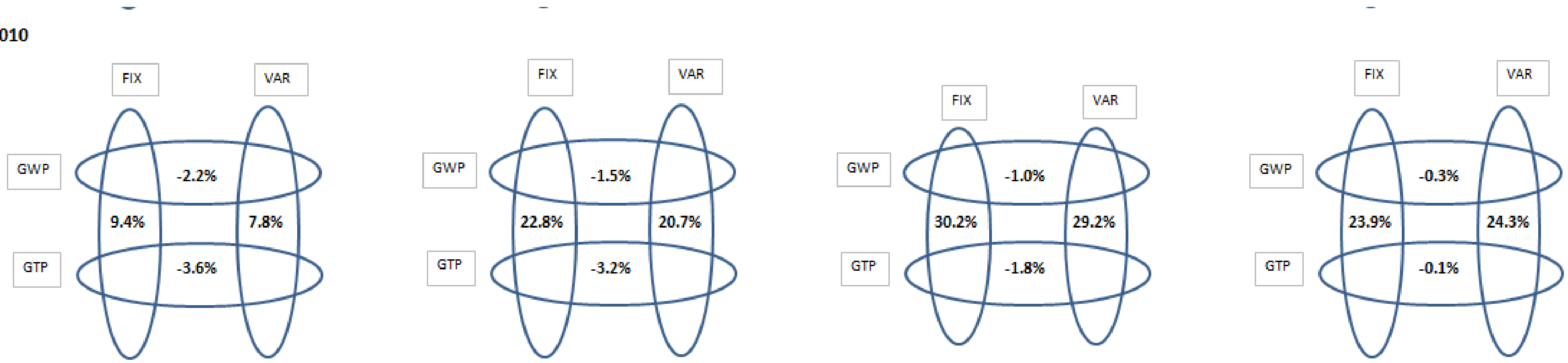

2020
2035
2050
2100
BEB 1970-2010
Energy: Fuel combustion
all period, all sectors
FIX
VAR
GWP
GTP
1.4%
1.5%
2.4%
2.3%
0.9%
3.0%
3.2%
1.1%
0.6%
3.5%
3.4%
0.4%
0.2%
2.8%
2.7%
0.1%
BEB 1970-2010
Energy: Fuel combustion
one year 2010, all sectors
-1.2%
0.9%
0.2%
-1.9%
-0.8%
1.7%
1.2%
-1.3%
-0.5%
2.1%
1.9%
-0.6%
-0.2%
1.7%
1.8%
-0.1%

BEB 1970-2010
Energy: Fuel combustion
all period, charcoal sector

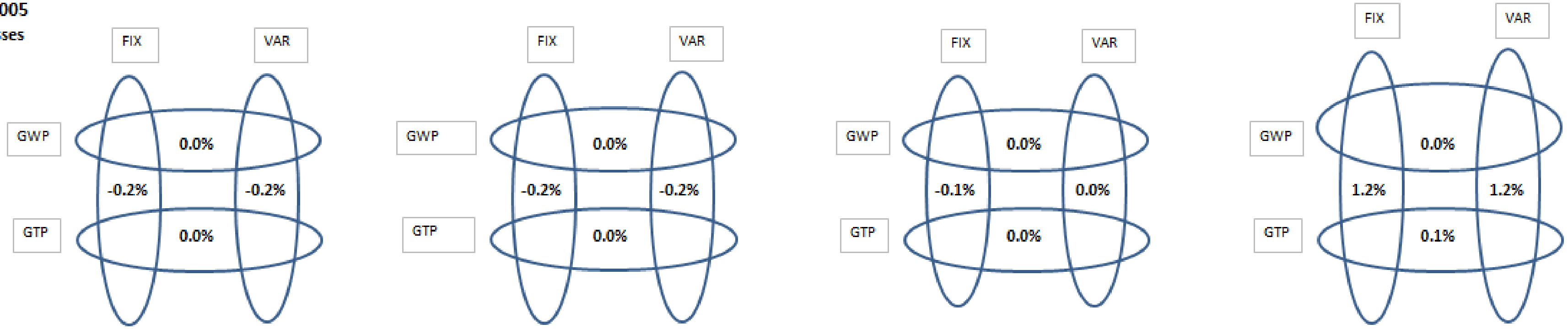



2020
2035
2050
2100
MCT II 1990-2005
Energy:fuel combustion
FIX
VAR
GWP
GTP
0.4%
1.5%
1.7%
0.6%
0.2%
2.9%
3.0%
0.3%
0.1%
3.4%
3.4%
0.1%
0.1%
2.7%
2.6%
0.0%
MCT II 1990-2005
Energy: Fugitive
1.2%
9.3%
10.5%
2.3%
0.8%
22.6%
23.2%
1.3%
0.6%
29.9%
29.8%
0.5%
0.2%
23.6%
23.4%
0.0%

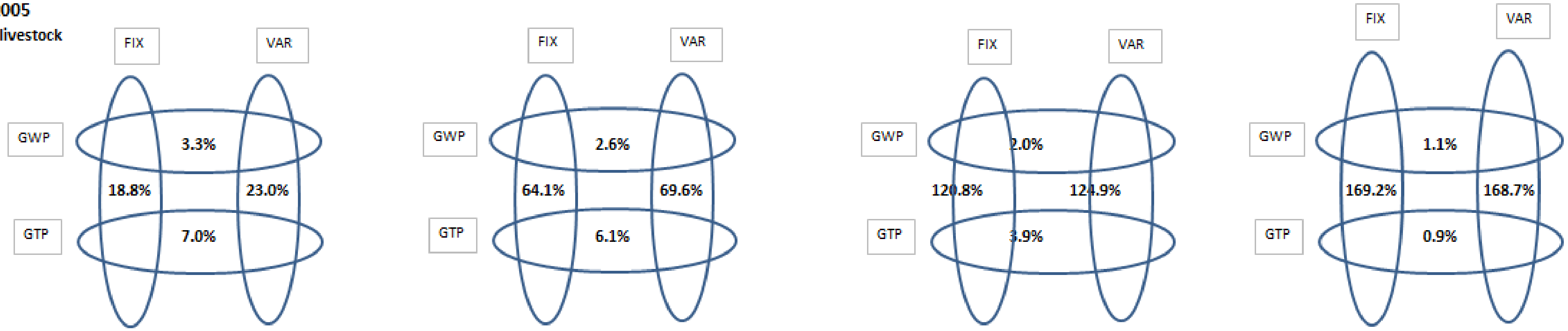
MCT II 1990-2010
Energy: Fugitive



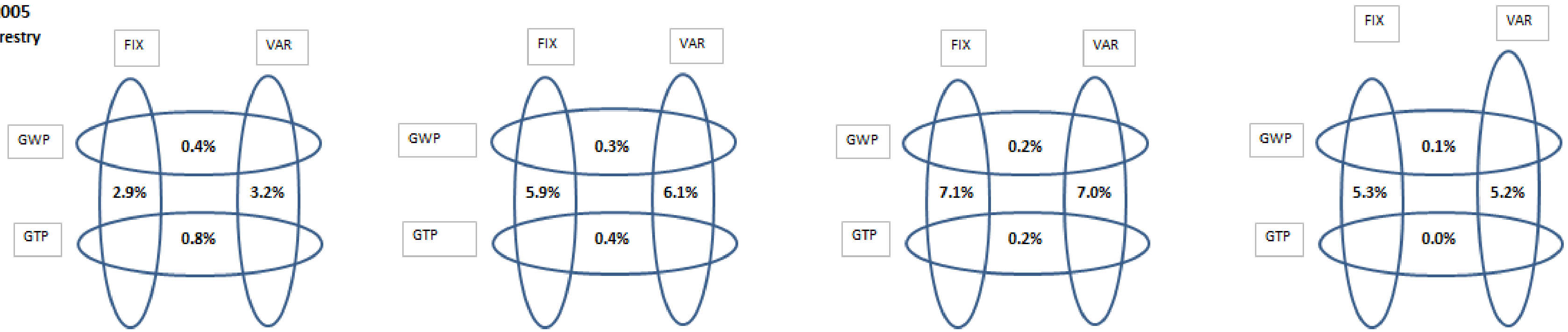
MCT II 1990-2005
Industrial processes



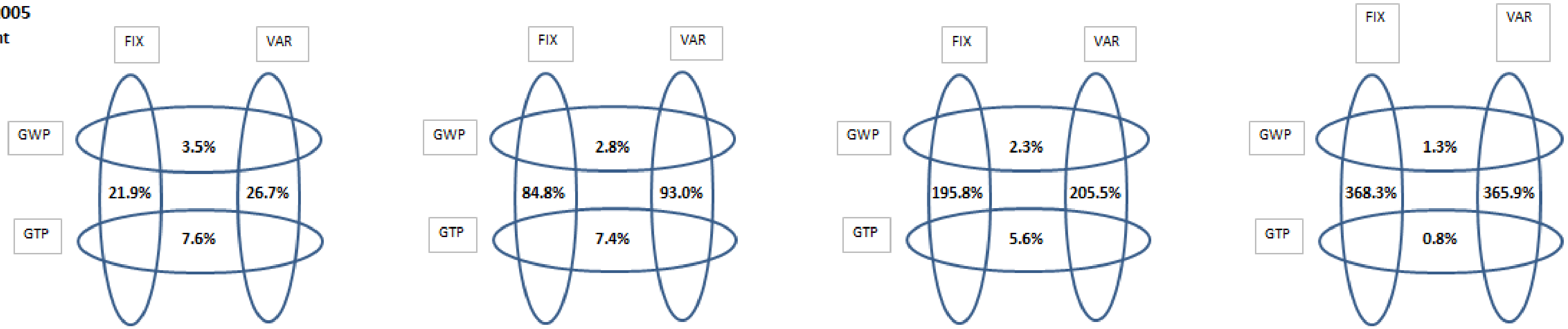
MCT II 1990-2005
Agriculture and livestock



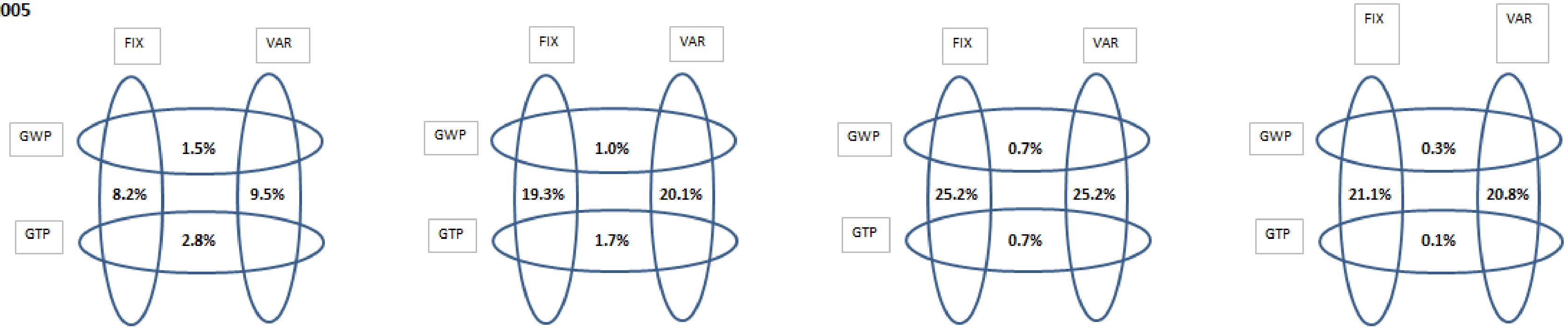
MCT II 1990-2005
Land-use and forestry



MCT II 1990-2005
Waste treatment



MCT II 1990-2005
All sectors



This chapter presented the CO_2-equivalents for all the scenarios, but did not analyze these results. The following chapter (Chapter 7) analyzes these results in detail by looking at the patterns in the resulting variations and searching for the factors underlying these patterns. This analysis required a methodology of its own, and therefore the decision was made to separate Chapter 6 from Chapter 7. Comparisons were performed between the various metrics for each time-horizon, and between the same metric for different time-horizons.

7. Analysis of results

The well-known limitations of GWP, in particular the awareness of the importance of the treatment of time, and the recent focus on GTP as an alternative metric, has given policymakers the possibility of choosing from a larger set of metrics. They may choose between GWP and GTP, as well as between the fixed and variable versions. A choice of time-horizon must also be made. What are the factors that should be considered in making this choice? The objective of the analysis conducted here is to use the CO_2-equivalency results presented in Chapter 6 to identify the main determining factors to be made in this choice.

In Chapter 3 we discussed general factors that come into play for the policymaker faced with a choice of multi-equivalency metric. Here we assume the policymaker has available a narrow set of metric choices, GWP and GTP, and must make decisions about time-horizon, about the relevance of the impact measured by the metric and about the need for a user-friendly transparent metric, in order to address policy questions such as the national responsibility for emissions and the establishment of sustainable developmental pathways.

In this analysis our main objective was to identify patterns of variation between the CO_2-equivalent emissions calculated based on the 16 different metrics (GWP versus GTP, fixed versus variable, 4 time-horizons). This variation is partially determined by the definition and general characteristics of the GWP and GTP metrics, but we also investigated the effect of the characteristics of the individual GHG emission scenarios on the variation. Some determinants of variation may be more significant for certain emission scenarios. The different combinations of individual GHG gases in each scenario allow various combinations of these determinants to emerge. The 10 scenarios (see Table 8) analyzed provided insights regarding how some of the characteristics of the metrics and of emission patterns determine overall variability. It should be noted that hypothetical scenarios could be tailored to bring out the interplay between determinants. The real scenarios, however, introduce elements which might not have been foreseen in hypothetical scenarios, and lead to more practical guidelines about expected variability when specific metrics are applied to sectors with different emission characteristics.

Since the main objective of this study is to investigate the consequences of methodological choices of multi-gas equivalency, the approach taken in this study is to first perform an analysis of the identified determinants and to compare the 16 metrics in light of the different determinants. Four determinants are considered. Two are based on characteristics of the GWP and GTP metrics and are independent of the emission scenarios: the GWP and GTP functions (Section 7.1), and the ratios between their values (Section 7.2). Two are based on the emission scenarios: the shape of the emission series as reflected in the offset of the series' center of mass relative to the reference year 2000 (Section 7.3), and the absolute contribution of each GHG in the multi-gas basket (Section 7.4).

Second, we draw on the scenarios as examples of the interaction between the determinants and perform a comparative analysis of the four metrics (Section 7.5).

One limitation of this analysis is the following. For the percentage differences between the metrics to be of practical use, they should be contrasted to the uncertainties in the emissions data used to produce the results. Results for the fuel combustion and for the industrial sector, for instance, for which emissions data is more accurate, can be expected to be more reliable than results for the agriculture and livestock sector, the land-use and forestry sector and the waste sector (see results of studies summarized at the beginning of Section 5.2). This consideration is especially important when comparison uncertainties are small. The objective of this study was limited to the determination of the variability between the metrics given the available data, yet when uncertainties are small, they are still useful in the context of this study, since they illustrate general trends in the relationship between the metrics.

7.1. Characteristics of GWP and GTP absolute values as functions of the time-horizon

In this section we first briefly look at the evolution of GWP and GTP values over time. Then we present the values calculated in this study using the Boucher and Reddy model and investigate some of the main characteristics of the functions.

There have been many studies estimating GWP values. The table below shows the evolution of GWP values reported by the IPCC, as well as GWP and GTP values from the literature.

Table 24– Evolution of GWP and GTP estimates.

		CH_4			N_2O			Research progress
		20	100	500	20	100	500	
GWP	IPCC FAR (1990)	64	21	9	270	290	190	Direct radiative forcing.
	IPCC SAR (1995) (*1)	56	21	6.5	280	310	170	Indirect cooling, atmospheric lifetimes, carbon cycle
	IPCC TAR (2001) Ramaswamy et al. (2001)	62	23	7	275	296	156	Positive feedback for indirect effects of methane emission on ozone and stratospheric water vapor concentration and on the methane lifetime.
	IPCC AR4 (2007) Forster et al. (2007)	72	25	7.6	289	298	153	Stratospheric water vapor, black carbon, sulfates, organic carbon, mineral dust, aerosols, aircraft, cloud and surface albedo, solar irradiance. Key uncertainties: clouds, cryosphere, oceans, land use, coupling between climate and biogeochemical cycles
	Boucher et al., (2009) (*3)	72.4-73.2	26.4-27.7	9.0-10.4	-	-	-	Indirect effect of CO_2 from CH4 oxidation
	This study (*2)	73.7	25.4	-	288.4	299.0	-	

GTP	Boucher et al., (2009) (*3)	58.1-59.0	5.3-6.7	3.1-4.4	-	-	-	Indirect effect of CO_2 from CH4 oxidation
	Fuglestvedt et al.(2010)	57	4	-	303	265	-	
	This study (*2)	60.0	3.9	-	300.9	266.1	-	

Notes:

(*1) The GWP-100 adopted by the Kyoto Protocol corresponds to the values published in the IPCC SAR

(*2) The lower value for GTP-100 for CH4 values are derived from the 2008 Boucher and Reddy formulations used as models in this study. They do not include the indirect effect of CO2 from CH4 oxidation reported in their 2009 study.

(*3) Boucher et al. (2009) show that GWP values are larger for all time-horizons when the production of CO2 from CH4 oxidation is accounted for. For GWP-100 the increase due to this effect (10%) is of the same order as the GWP increase reported by the IPCC to have occurred between the Third and Fourth Assessments, which do not take this indirect effect into account. For GTP, this effect increases GTP-100 by approximately 50%.

In this study, GWP and GTP values were calculated for CH_4 and N_2O for time-horizons in the 2-150 range, according to the formulations presented in Sections 4.4.4 and 4.4.5[53].

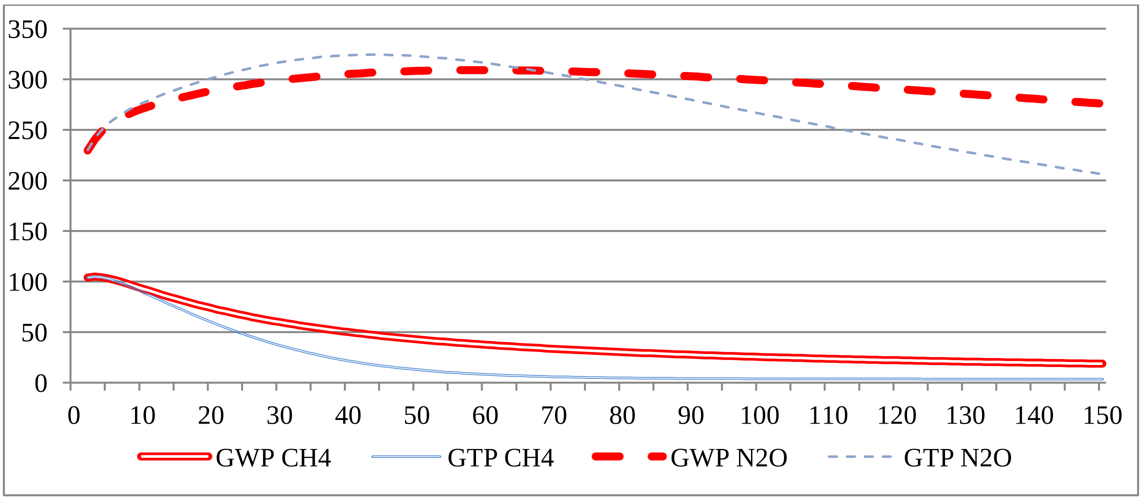


Figure 30 – Plot of GWP-TH and GTP-TH values, for time-horizons TH from 2 to 150.

According to Figure 30, the following trends in the GWP and GTP functions are especially relevant:

For CH_4

- Range of values in 2-150 time-horizon range:

[53] These calculations were performed using a MATLAB platform. The code uses functions and databases developed at the Center for International Climate and Environmental Research, Oslo (CICERO) and parameters from Fuglestvedt et al. (2010).

    - GWP: 18.7 to 104.8
    - GTP: 3.4 to 104.8
- GWP and GTP functions are both decreasing
- The GTP function decreases faster than the GWP function, particularly for time-horizons smaller than 50.
- Up to time-horizon 51, the difference between GWP and GTP increases. Beyond that point, the difference decreases, as both functions approach 0 asymptotically.

For N_2O

- Range of values in 2-150 time-horizon range:
    - GWP: 229.7 to 309.1
    - GTP: 206.0 to 324.2
- Both GWP and GTP have maximums.
    - GWP maximum of 309.1 occurs at TH of 59
    - GTP maximum of 324.2 occurs at TH of 44
- GTP is larger than GWP until approximately TH=70.

7.2. Characteristics of ratios of the GWP and GTP metrics as function of time-horizon

The CO_2-equivalent for individual gases depends solely on the emission of the GHG, and on the metric multiplier, while for multiple gases, the CO_2-equivalent depends as well on the proportion of the mix. For an individual gas, the emissions based on a fixed metric will always vary with time-horizon in the same proportion as the ratio of the metric multipliers. As an example, the GWP-20, GWP-35 and GWP-50 emissions for CH_4 will always be 2.9, 2.14 and 1.68 times the GWP-100 based emissions, respectively. These selected ratios are necessary for a comparison of fixed GWP and GTP.

Table 25 – Ratio of GWP-TH and GTP-TH to GWP-100 and GTP-100, based on parameters in Shine, Fuglestvedt, et al. (2005).

TH	CH_4		N_2O	
	GWP-TH/GWP-100	GTP-TH/GTP-100	GWP-TH/GWP-100	GTP-TH/GTP-100
20	2.90	15.55	0.96	1.13
35	2.14	7.33	1.01	1.21
50	1.68	3.32	1.03	1.21
100	1.00	1.00	1.00	1.00

Plots of the ratios between the metrics are shown in Figure 31.

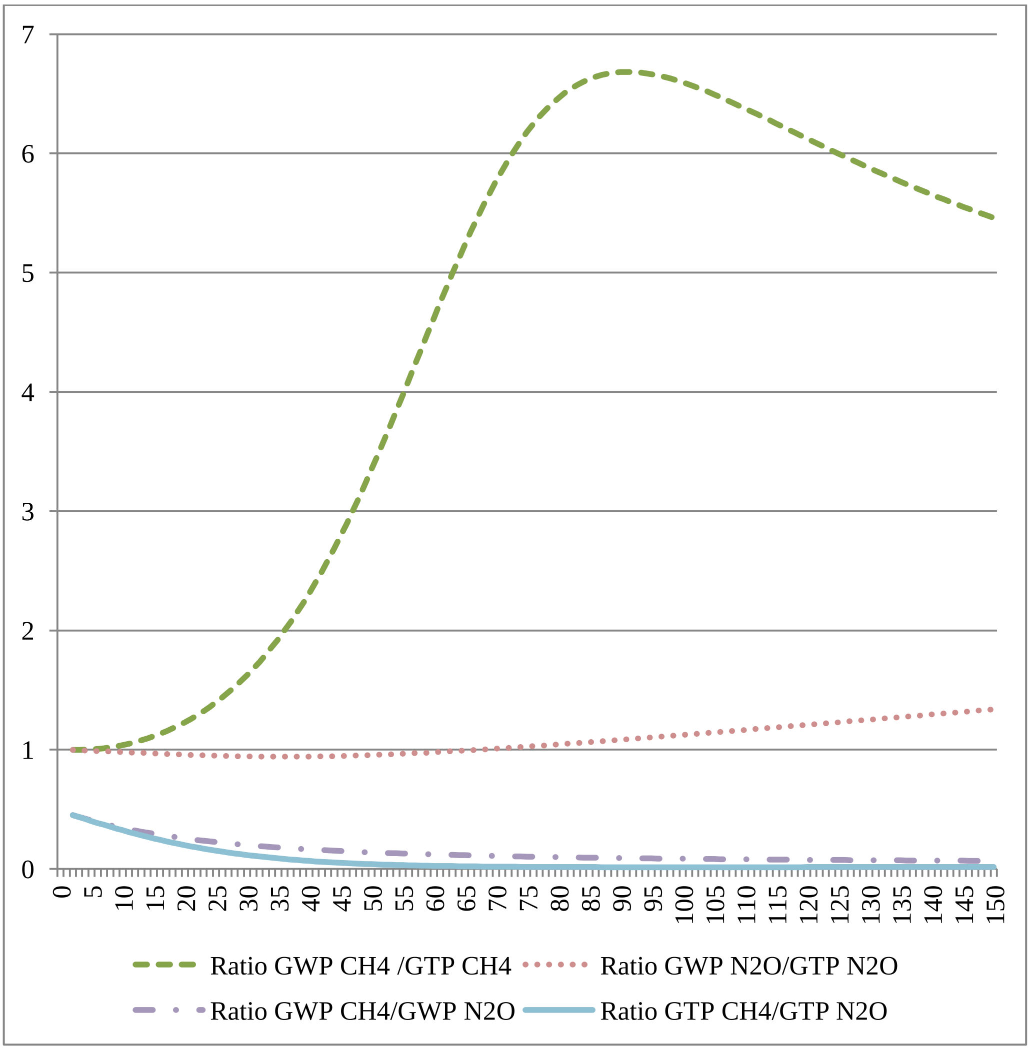


Figure 31 – Plot of ratio of GWP and GTP metrics for CH_4 and N_2O as function of time-horizon.

The following trends are especially relevant:

GWP/GTP

- For CH_4, the ratio increases rapidly until the maximum at TH = 91, where the GWP for CH_4 is almost 7 times that for N_2O. After TH=91, the ratios decreases slowly, so that at TH=150 GWP for CH_4 is approximately 5 times larger than for N_2O.

- For N_2O, the ratio increases very gradually and does not peak. Therefore the weight of CH_4 relative to N_2O becomes more important as the TH gets larger. Only at TH=100 does N_2O recover some of its relevance, as the function increases more rapidly after approximately TH=68.

- Since the ratios are significantly larger at the TH=100 for CH_4, compared to smaller THs, the difference between the metrics is sensitive to the contribution of CH_4 in the mix of gases.

The values of the ratios of GWP to GTP that are relevant for this study are summarized below.

Table 26 – Ratio of GWP to GTP for CH_4 and N_2O, for 4 time-horizons.

	Time-horizon	fixed GWP/ fixed GTP
CH_4	100	6.60
	50	3.34
	35	1.93
	20	1.23
N_2O	100	1.12
	50	0.95
	35	0.94
	20	0.96

GWP CH_4/GWP N_2O

- The ratio is less than 1, meaning that GWP is larger for N_2O for the entire period
- The ratio is decreasing, meaning that GWP for N_2O gets relatively larger as time-horizon gets larger.
- Range is 0.07 to 0.45, meaning that GWP for N_2O is a little more than twice as large as the GWP for CH_4 for small time-horizons and almost 15 times as large at time-horizons close to 150.

GTP CH_4/GTP N_2O

- The ratio is less than 1, meaning that GTP is larger for N_2O for the entire period
- The ratio has a minimum of 0.014 at TH=100, meaning that GTP for N_2O is at most about 70 times larger than GTP for CH_4.

The values of the ratios that affect the analysis are summarized below.

Table 27– Ratio of GWP of CH_4 to GWP of N_2O, and ratio of GTP of CH_4 to GTP of N_2O, for 4 time-horizons.

Time-horizon	**20**	**35**	**50**	**100**
GWP CH_4/GWP N_2O	0.26	0.18	0.14	0.09
GTP CH_4/GTP N_2O	0.20	0.09	0.04	0.01

7.3. Center of emission mass, offset and normalized real impact: methodology and application to BEB and MCT II series

7.3.1. Definition of center of emission mass, offset and normalized real impact

When fixed GWP or GTP metrics for an emission series are calculated, it is relevant to know by how many years the emission 'center of mass' is offset relative to the reference year 2000`.

For a specific impact year, comparisons between fixed metrics and variable metrics may be distorted if this offset is ignored. Variable metrics discount every emission pulse correctly, while commonly used fixed metrics only discount correctly for a specific year if the aggregate pulse was emitted in the year 2000. It is therefore important to investigate how much underestimation or overestimation the use of the fixed GWP and GTP leads to.

If we are to consider the actual impact of the fixed GWP-TH or GTP-TH metric at a fixed time-horizon TH, then all the emission pulses would have to have originated as one aggregate pulse (the sum of all individual pulses) at a moment x years *before* the time-horizon. For instance, to compare the impact of an emission pulse in 2100, the GWP-100 fixed metric will only discount correctly if the emission pulse occurred in the year 2000. If a series is skewed to the right of the year 2000, as can be the case in an increasing emission series, the impact given by the GWP-100 metric will not be that corresponding to the impact in 2100, but to a moment beyond 2100.

When multi-gas comparisons are made for regions or economic sectors, emissions are often summed using various methodologies, depending on data availability, and on the particularities of the case in question. The mean of the emissions will not generally occur in the year 2000. When comparing multi-gas emissions with just one kind of metric, as is the case in policymaking, this is not a problem. But if we wish to compare fixed and variable metrics for the same emission series, the impact of each kind of metric at a specific time in the future should take into account over- or underestimations. We define here the 'emission center of mass' (ECM) of a series of gas x according to Equations 34 and 35. The ECM defined here is equivalent to the first moment of the normalized emissions, about the origin of the time-series, over a discrete time domain

$$\sum_{t=t_i}^{t=t_f} E_x(t).(d_t - TC_x) = 0$$

Equation 34

$$\boldsymbol{TC_x = \frac{\sum_{t=t_i}^{t=t_f} E_x(t).d_t}{\sum_{t=t_i}^{t=t_f} E_x(t)}}$$

Equation 35

where

TC_x = center of emission mass of gas *x* relative to t_i , in years, rounded off.

t_i= year corresponding to start of emission period

t_i = year corresponding to end of emission period

d_t =time lapse between emission at end of year t and beginning of year t_i, where we assume that d_{t_i} = 1.

$E_x(t)$= emission pulse of gas *x* aggregated at end of year *t* in mass units

There will be an offset between the ECM of the period and the year 2000. We define the offset to be negative if the ECM occurs before the year 2000, and positive if it occurs afterwards. For an emission series $E_x(t)$ for non-CO_2 gas x, for period t_i to t_f, with center of mass emission TC_x years after the beginning of the series, the definition of the offset relative to the reference year 2000 is defined as:

$$offset\left(t_i, t_f, E_x(t)\right) = t_i + TC_x - 2000$$

Equation 36

For example, for the 1970-2010 period, t_i = 1970, t_f = 2010 and d_{1970}=1, d_{1971}=2 … d_{2010}=41

For CH_4 emissions from the BEB series in this period (see Figure 8), we find that TC_{CH4} is approximately 20 years (19.83), so the ECM occurs in 1990 and the offset is therefore 1970+20-2000 = -10.

As a measure of the effect of the offset, the ratio of the real or actual impact at the time-horizon (in numerator) to the assumed or expected impact (in denominator) was calculated for each non-CO_2 gas. This corresponds to normalizing the corrected GWP and GTP multipliers at the time-horizon by the corresponding fixed multiplier. We call this ratio *the normalized real impact* (NRI). It is a function of the time-horizon (here t=20, 35, 50 or 100) and the ECM of the emission series, but is independent of the values emission series. The NRI for the GWP of gas x is the following:

$$NRI_{x,GWP}(t, offset) = \frac{GWP_x(t - offset)}{GWP_x(t)}$$ **Equation 37**

$$NRI_{x,GTP}(t, offset) = \frac{GTP_x(t - offset)}{GTP_x(t)}$$ **Equation 38**

The closer the NRI is to 1, the smaller the distortion between the real and assumed impacts. When the NRI is 1, there is no distortion. When comparing the impacts of an emission series using fixed and variable metrics, the fixed metric value should first be multiplied, or discounted, by the NRI of the series.

The following table summarizes the definition of the three indicators, ECM, the offset and the NRI.

Table 28 – Definition of ECM, offset and NRI indicators.

Indicator	Unit	Definition	
Emission center of mass (ECM)	Specific year	First moment of the normalized emissions, about the origin of the time-series, over a discrete time domain	
Offset	Period of years	Number of years between ECM and year 2000	<0 :ECM to left of 2000
			=0 : ECM at 2000
			>0 : ECM to right of 2000
Normalized real impact (NRI)	Dimensionless	Ratio of the real impact at the time-horizon to the assumed or expected impact	<1 : Overestimation of impact
			=1 : No distortion
			>1: Underestimation of impact

As an illustration of the range of effect the offset of an emission series may have on the use of fixed GWP and GTP, the NRI with an offset range of 25 years[54] in either direction around the year 2000 was investigated. The normalization was only performed for 2050 and 2100, as these time-horizons illustrate the offset effect quite well. Since CO_2 is the reference gas, this offset has no effect. The NRI for CH_4 and N_2O, for GWP and GTP, are shown in Figure 32.

The general trends of the normalization results are a direct consequence of the characteristics of the GWP and GTP functions, as shown in Figure 30.

When the offset is negative, which corresponds to the center of emission mass occurring before the year 2000, the NRI is less than unity for both GHGs and both time-horizons, for both the GWP and GTP functions (see Figure 30) are descending in a 25-year range around the fixed metrics GWP-50 or 100 and GTP-50 or 100. There are two ways to interpret the consequences of this. First, looking at 2100, the real impact in 2100 is less than the expected impact because the correct multiplier for 2100 is smaller than the GWP-100 or GTP-100 multiplier. Second, the expected impact given by the GWP-100 or GTP-100 multiplier occurs before 2100, at a date equal to 2100 minus the number of offset years. The consequences of these differences must be contemplated in policymaking. It is not an uncommon mistake in negotiation contexts to assume that the

[54] This range was chosen for illustrative purposes.

use of GWP-100 provides the impact in the year 2100. An impact expected to occur in 2100 will therefore occur before that date, and will have attenuated by 2100. In such cases, the NRI is a transparent and useful measure of over- or underestimation of the impact in the year under consideration.

As an example, for CH_4 emissions with a ECM in 1975, the GWP multiplier which accounts for the actual distance of the 1975 aggregated pulse until 2100 (GWP-125) is 21.4, while GWP-100 is 25.4, so the real impact in 2100 is a fraction of the impact assumed by the policymaker, in this case 84%. The assumed impact as measured by the GWP-100 occurs in 2075.

In the following analysis we look at the extremes of the plots, at offsets of -25 and 25, thus determining the worst cases for that range. All NRI values mentioned are for these boundary cases.

General results for a 25-year offset period around the reference year 2000 are summarized in the table below.

Table 29 – Range of normalized real impact (NRI) when emission center of mass occurs before and after reference year 2000, for time-horizons 2050 and 2100, for ±25 year offset period.

Time-horizon		GHG	ECM occurs before 2000 Offset ≤ 0		ECM occurs after 2000 Offset ≥ 0	
			GWP	GTP	GWP	GTP
2100	$NRI = \frac{metric_x(100-offs}{metric_x(100)}$	**CH_4**	0.84 - 1	0.93 - 1	1 - 1.25	1 - 1.33
		N_2O	0.96 - 1	0.88 - 1	1 - 1.03	1 - 1.12
2050	$NRI = \frac{metric_x(50-offse}{metric_x(50)}$	**CH_4**	0.74 - 1	0.40 - 1	1 - 1.55	1 - 3.71
		N_2O	≈1	0.93 - 1	1 - 0.95	1 - 0.96
			$NRI = \frac{real\ impact}{assumed\ impact} \leq 1$		$NRI = \frac{real\ impact}{assumed\ impact} \geq 1$ Exception: N_2O in 2050	

Notes: The closer the NRI is to 1, the smaller the distortion between the real and assumed impacts.

We observe the following for the boundary case of a 25 year offset range (see Figure 30 for all references to GWP and GTP functions, and Figure 32 for the NRI functions):

- For an ECM occurring *before* 2000,
  - CH_4
    - The distortion for GWP (solid lines) is largest for CH_4 in 2050 (NRI=0.74) than in 2100 (NRI=0.84), because the GWP function falls off more rapidly in the vicinity of GWP-50 (between GWP-50 and GWP-75) than near GWP-100 (between GWP-100 and GWP-125).
    - The distortion for GTP (dotted lines) is significantly larger for CH_4 in 2050 (NRI=0.40) because the GTP function falls off even faster in the vicinity of 2050 than the GWP function. For CH_4 in 2100, the distortion for GTP is small (NRI=0.93) because the GTP function is quite flat in the vicinity of 2100.
  - N_2O
    - The distortion for GWP is very small for N_2O for 2100 and 2050 because the N_2O function peaks at GWP-59 and is quite flat in the vicinity of GWP-50 and 100.

        - The distortion for GTP is small but not insignificant for N_2O (0.88 for 2100 and 0.93 for 2050) because the N_2O function starts to fall off after the peak at GTP-44
- For an ECM occurring *after* 2000:
    - CH_4
        - The distortion for GWP is largest for CH_4 in 2050 (1.55) than in 2100 (1.25), again because the GWP function falls of more rapidly in the vicinity of GWP-50 than near GWP-100.
        - The distortion for GTP is at its largest for CH_4 in 2050 (3.71), compared to in 2100 (1.33) because the GTP function is falling off at its fastest rate approximately between GTP-25 and GTP-50. The result for GTP for CH_4 in 2050 should be highlighted as the most significant result of the analysis.
    - N_2O
        - When the GWP and GTP functions are descending and the offset is positive, the NRI is larger than unity. This is the case for CH_4 for any time-horizon, and for larger time-horizons for N_2O. For N_2O in 2050 there is an exception, for the N_2O functions are ascending up until GWP-59 and GTP-44. This results in NRIs less than unity for N_2O for both negative and positive offsets. The consequences here are that the real impact of N_2O in 2050 is less than the expected impact regardless of where the ECM is located.

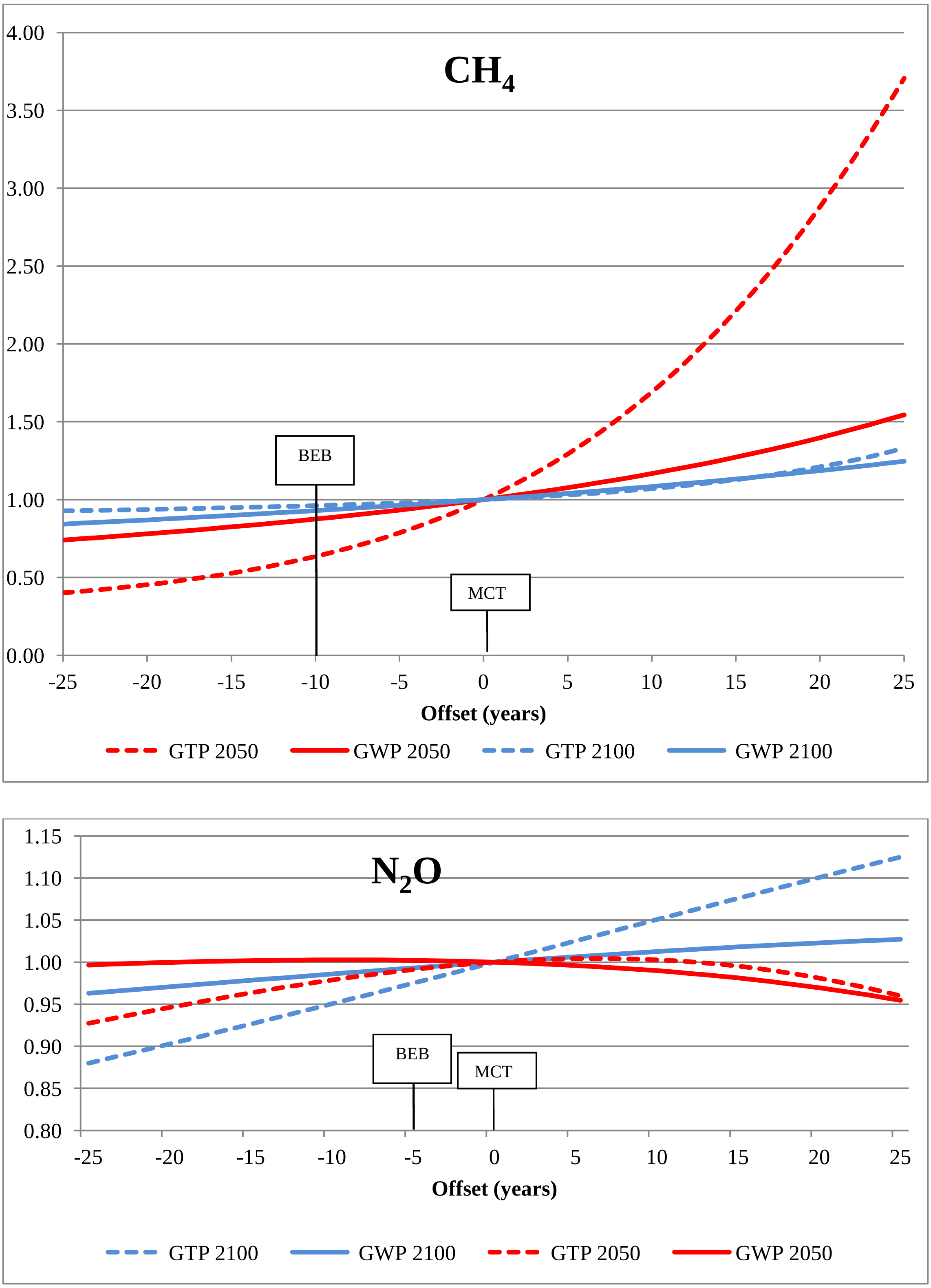


Figure 32 - Normalized real impact (NRI) when emission center of mass occurs before and after reference year 2000, for time-horizons 2050 and 2100, for CH_4 and N_2O, and for fixed GWP and GTP. Boxes with BEB and MCT indicate where the ECM occurs for the BEB and MCT series, as calculated in the next section.

Summarizing, for policymaking and for metric comparison in this study, the cases that are most significant are when there is an underestimation of the real impact of the metric. *For CH_4, the worst distortion occurs for impacts in 2050 when GTP is used, but the distortion for GWP and for 2100 are also significant; for N_2O impacts in the year 2100 are the worst, but are not significant.* When there is overestimation of impacts, the consequences for policymaking are likely not to be as serious, as more conservative policies will be designed. Nonetheless, for metric comparison cases, these distortions should be taken into account.

7.3.2. Center of emission mass, offset and normalized real impact of BEB and MCT II series

The emission center of mass, offsets and normalized real impacts, as defined in Section 7.3.1., were calculated for the BEB and MCT II emission series and are summarized in Table 30 and Table 31.

For the BEB series, the emission centers of mass for CH_4 and N_2O are 1990 and 1994, respectively. The BEB series is an adequate series for comparison of fixed and variable metrics, since the NRIs are close to 1, with an exception for CH_4 in 2050 and at closer time-horizons, where the underestimation for GWP and GTP are larger, as was noted in the previous section. For GTP, the difference is particularly significant for the real GTP-based impact is on the order of 60% of the assumed impact in 2050 and closer time-horizons. When the fixed and variable metrics are compared for the BEB series, this underestimation will have to be taken into account for CH_4 GTP in 2050, 2035 and 2020.

Table 30 – Normalized real impact for BEB emission series for CH_4 and N_2O for time-horizons 2050 and 2100..

Time-horizon	GHG	NRI for BEB emissions (1970-2010)	
		GWP	GTP
2100	CH_4	0.93	0.96
	N_2O	0.99	0.97
2050	CH_4	0.88	0.64
	N_2O	1.00	0.99
2035	CH_4	0.85	0.58(*1)
	N_2O	1.02	1.01
2020	CH_4	0.81	0.61 (*1)
	N_2O	1.04	1.05

Notes:
For CH_4, TC=19.8, ECM=1990, offset= -10.2
For N_2O, TC=23.8, ECM=1994, offset= -6.2
Highlighted values could be significant in comparing fixed metrics with others.
(*1) The correct result is that the NRI is smaller at 2020 than at 2035. Because the GTP and GWP values are calculated only for discrete values, we rounded off the offsets. Here the 10.2 year offset was rounded off to 10, and at 2035 a 0.2 error corresponds to a steeper slope of the GTP function than the same error at 2020, explaining why the NRI shown here for 2020 is larger than for 2035

For the MCT II emission series, the emission center of mass occurs in 1999[55] for both GHGs, very close to the reference year 2000. There is no significant underestimation of impacts for any of the 4 time-horizons, the largest being 5% for CH_4 GTP in 2020. The MCT II series is therefore an adequate series for comparison of fixed and variable metrics.

Table 31 - Normalized real impact for MCT II emission series for CH_4 and N_2O for time-horizons 2050 and 2100

Time-horizon	GHG	NRI for MCT II emissions (1990-2005)	
		GWP	GTP
2100	CH_4	0.99	1.00
	N_2O	1.00	0.99
2050	CH_4	0.99	0.95
	N_2O	1.00	1.00

Notes:
For CH_4, TC=9.0, ECM=1999, offset= -1.0
For N_2O, TC=9.0, ECM=1999, offset= -1.0

[55] If emissions were constant, the ECM would be in the middle of the period, in 1998. Although emissions generally increase during the period, there is a local peak in 1995 for both GHGs, which brings the ECM closer to the beginning of the period.

7.4. Contribution of individual GHGs in total emissions

Another determinant which affects the variation in CO_2-equivalency using different metrics is the relative proportion of the GHGs to each other. These effects depend on the particular combination of GHGs in the multi-gas basket, but it is relevant to take into consideration the absolute proportions of the GHGs as an indicator. When CO_2 emissions are the main contribution, CH_4 and N_2O metric values do not play a significant role and the CO_2-equivalent values vary little. Yet a slightly larger contribution of N_2O, for instance, can lead to significant differences in the metrics, due to large N_2O metric values.

Table 32 – Contribution of individual GHGs in total emissions of BEB and MCT II series, by sector.

		CO_2	CH_4	N_2O	Total
BEB 1970-2010 (Mt)	**Energy: Fuel combustion: all period, all sectors**	9217.39	11.46 (0.12%)	0.56 (0.006%)	9229.40
	Energy: Fuel combustion: one year 2010, all sectors	394.25	0.29 (0.07%)	0.02 (0.005%)	394.56
	Energy: Fuel combustion: all period, charcoal sector	0	0.49 (88.24%)	0.07 (11.76%)	0.56
MCT II 1990-2005 (Mt)	**Energy: Fuel combustion**	3,872.77	4.63 (0.12%)	0.15 (0.004%)	3,877.40
	Energy: Fugitive 1990-2005	151.26	1.73 (1.13%)	0	152.99
	Energy: Fugitive 1990-2010	221.75	2.57 (1.15%)	0	224.33
	Industrial processes	904.61	0.12 (0.01%)	0.27 (0.03%)	905.00
	Agriculture and livestock	0	172.19 (96.52%)	6.21 (3.48%)	178.40
	Land-use and forestry	18,860.36	46.04 (0.24%)	0.32 (0%)	18,906.72
	Waste treatment	1.19	24.39 (94.65%)	0.19 (0.72%)	25.77
	All sectors	23,790.20	249.08 (1.04%)	7.15 (0.03%)	24,046.43

7.5. Comparison between metrics

The analysis in this section is based on the results presented in Chapter 6. The percentage variations between the metrics used in this comparison are shown in the tables and graphs of that chapter and are also summarized pictorially in Section 6.3, which show 4 diagrams (one for each time-horizon) for each sector.

The main questions to be answered here are: How do the metrics compare in the context of the multi-gas emission scenarios? If we are to choose a metric for a sector or a group of sectors, which one should it be? To answer these questions, we conduct four analyses: in Section 7.5.1 we assume a fixed metric must be used, and compare the fixed versions of GWP with GTP; in Section 7.5.2 we assume a variable metric must be used, and compare the variable versions of GWP and GTP; in Section 7.5.3 we assume GWP must be used and compare its fixed and variable versions; in Section 7.5.4 we assume GTP must be used and compare its fixed and variable versions. Finally, an overall comparison is made.

In these analyses, an effort was made to make a clear distinction between trends which are generally true, regardless of the emission scenario, and which trends are dependent on the particular scenario in question. Another distinction which should be kept clear is when a comparison is being made between the CO_2-equivalents of one gas or of the multi-gas mix.

7.5.1. Fixed GWP versus fixed GTP

This comparison is the most relevant of the 4, since fixed metrics are easier to use and fixed GTP is the most likely metric to be adopted either to compliment or replace fixed GWP (IPCC, 2009).3

For an individual GHG, the difference between fixed GWP and GTP at a certain time-horizon is determined by the ratio between the GWP and GTP multiplier at that time-horizon. This results from the definition of the fixed metric, which applies a multiplier to the aggregated emissions. The aggregated emissions are the same for either the GWP or GTP metric, so the difference between the metrics is due uniquely to the relationship between the multipliers. For gas x at time-horizon TH, we are comparing the following (see Equation 30):

$$\left[\sum_{t=t_i}^{t=t_f} E_x(t)\right].GWP_x(TH) \quad versus \quad \left[\sum_{t=t_i}^{t=t_f} E_x(t)\right].GTP_x(TH)$$ Equation 39

These ratio functions are shown for CH_4 and N_2O in the top two plots of Figure 31. The ratios for the 4 time-horizons are summarized in Table 26.

For multiple GHGs, the variation between the CO_2-equivalents as measured by fixed GWP or GTP depends on the sum of the emissions weighed by the multipliers:

$$\sum_x \left[\left(\sum_{t=t_i}^{t=t_f} E_x(t)\right).GWP_x(TH)\right] versus \sum_x \left[\left(\sum_{t=t_i}^{t=t_f} E_x(t)\right).GTP_x(TH)\right]$$ Equation 40

The contribution of each GHG determines approximately which multiplier ratios weigh more in the overall ratio. For time-horizons in the proximity of the peak at TH=91, as explained in Section 7.2, GWP values are almost 7 times GTP values, so if CH_4 emissions weighs significantly more, the GWP-TH/GTP-TH ratio for that GHG will predominate. N_2O ratios are close to unity, so N_2O contributions are not as significant.

In the following analysis, we are looking at the percentages shown in the left-hand side of each individual diagram in Section 6.3.

For the first case of Scenario 1 (BEB fuel combustion for the entire period and all sectors), the difference between fixed GWP and GTP is less than 3.5% (see Table 13 and associated Figure 19), mainly because the contribution of CH_4 and N_2O in fuel combustion is small. As can be seen in Table 32, CO_2 emissions are over 99% of total emissions. In spite of the small difference in results for these metrics, an analysis of this scenario is interesting for two reasons. First, it highlights the evolution of the difference between the metrics as the time-horizon increases, identifying trends that also occur in scenarios where the contribution of CO_2 is smaller, as will be discussed below (as was already pointed out, in the context of this study, small uncertainties still serve the purpose of illustrating trends in variability). Second, because the trends are evident even though the differences are less than 3.5%, this analysis is conservative, and therefore serves as evidence of the sensitivity of the metric differences to emission patterns.

Continuing the analysis of Scenario 1, the difference between fixed GWP and GTP increases from 1.5% to 3.0% to 3.5% as the time-horizon increases from 20 to 35 to 50, respectively. For N_2O for this time-horizon range, GTP is only slightly larger than GWP (see Figure 31), and the ratio function is almost flat. Therefore the percentage difference in this range is due mostly to CH_4 emissions. Since in this time-horizon range the CH_4 ratio function increases fast (maximum is at TH = 91), GWP values grow faster than GTP values, causing the total GWP to GTP difference to increase from 1.5% to 3.5%. At a time-horizon of 100, however, there is a reversal of this trend, for the total percentage difference decreases to 2.8%. The reason for this reversal is that both CH_4 and N_2O multipliers are smaller at TH=100, so CO_2 acquires a bigger weight in the total, decreasing the total percentage difference. Since CO_2 emissions are the same for either metric, and at the same time contribute more to the total, they offset the CH_4 and N_2O trends which would tend to increase the percentage difference in the total.

For the second case of Scenario 1 (BEB fuel combustion for the isolated year 2010 -see Table 15 and associated Figure 20), the variability between the metrics is also insignificant, yet the same trends, as discussed for the entire period, are observable. There is an increasing percentage difference up to TH=50 and then a decrease.

For Scenario 1B (fugitive emissions for 1990-2010), CH_4 emission are a slightly larger contribution, over 1%. It is important to observe that an absolute contribution of this seemingly small magnitude has a noticeable effect, especially at close time-horizons, because of the large CH_4 and N_2O multipliers. The same trend, of increasing percentage differences up to TH=50 and then a decrease, is again identified here, for the same reasons already discussed. Yet since the absolute contributions of CH_4 and N_2O are larger than for Scenario 1, the percentage differences are also larger, increasing from almost 10% for TH=20 to 30% for TH-50, and then decreasing to 24% for TH=100.

We conclude that even when CO_2 emissions are almost 100%, the effect of the proportions of CH_4 and N_2O in the difference between fixed GWP and GTP is noticeable, even at small time-horizons.

For the third case of Scenario 1, BEB fuel combustion for the isolated charcoal sector, CO_2 emissions are zero[56]. This case allows the effect of the two non-CO_2 gases, as already described above in the case of the full period emissions (Scenario 1, Case 1), to emerge clearly. As the time-horizon gets larger, CH_4 GWP increases faster than GTP, while for N_2O the ratio stays close to unity. Although both GWP and GTP multipliers become smaller for CH_4, since there is no constant CO_2 contribution to offset this trend, the difference between the metrics is almost completely determined by the CH_4 in the total emission mix (approximately 88%). The percentage differences between fixed GWP and GTP increase from 12% for TH=30 to 66% for TH=100. Here there is no reversal trend, as in the first and second cases of Scenario 1, since there is no CO_2 contribution. The full effect of the metrics on CH_4 emerges, leading to significant differences between the metrics.

The presence of N_2O appears at first glance to have a minor effect on this trend, as its contribution is only 12% of the total. But because of the high multiplier values, the relatively constant contribution of N_2O as the time-horizon increases radically offsets the CH_4 trend. To see this, the charcoal sector's emissions listed by the updated MCT II were analyzed, for the N_2O emissions are zero and the sector only emits CH_4. We observed that for this case the fixed GWP is more than twice the fixed GTP for TH=50, and more than 5 times for TH=100.

Looking now at Scenario 2 (MCT II emissions), the industry sector's CH_4 and N_2O contributions are insignificant. Because CO_2 multipliers are unity, there is practically no difference between the fixed GWP and GTP metrics here.

The land-use sector, and all sectors regarded as a whole, both exhibit the same trend discussed above (increasing percentage differences up to TH=50 and then a decrease) because the CH_4 and N_2O contributions are on the order of 0.5 to 1%, neither insignificant nor very large. For land-use the differences are less than 8%. For all sectors, the differences increase from 8% to 25% for TH=50, and then decrease to 21%, differences large enough to possibly merit attention.

[56] The charcoal sector combusts biomass, so CO2 emissions are considered to cancel out, as recommended by the IPCC guidelines. For CH4, a conservative scenario for charcoal was analyzed, with an IPCC emission factor of 30 kg/TJ for the energy sector, as opposed to MCT scenario, which uses 300 kg/TJ.

Two sectors, the agricultural sector and the waste sector, show very large differences in the two metrics, for CO_2 emissions are close to zero. These cases are akin to the charcoal sector described above, but since the CH_4 contribution is even larger, almost 95% of the total, this is reflected in a large difference between the metrics at TH=100: for agriculture, the GWP CO_2-equivalent value is more than 2.5 times that obtained from the use of GTP, and for waste the GWP is almost 4 times the GTP value.

When the effect of the ECM of the BEB series is taken into account here, the only overestimation that is significant is for CH_4 GTP for time-horizons at or before 2050 (see Table 30 – Normalized real impact for BEB emission series for CH4 and N2O for time-horizons 2050 and 2100). To be exact, the NRIs should be applied to the variability results for each GHG before they are summed to produce the CO_2-equivalent value. For the BEB scenarios studied, when all sectors are taken into account, CH_4 contribution is small, so applying a NRIs makes a difference of less than 1% for the multi-gas CO_2-equivalent. Applying NRIs to the charcoal sector, however, the only CH_4-intensive BEB scenario investigated, leads to overestimations of the order of 10% for the closest time-horizon (2020), and less than 10% for the further time-horizons. Since according to the MCT the charcoal sector's emissions embed considerable uncertainty (MCT, 2010) due to the difficulty of data collection, we assume that overestimations of less than 10% are not significant.

The data from the other CH_4 intensive sectors, agriculture and waste, was derived from MCT II emissions, where the ECM is very close to the reference year 2000, resulting in insignificant discounts of less than 1%.

Table 33 summarizes the sectoral trends discussed above. Categories were chosen so as to highlight the effects of the mix of the GHGs on the variability between the fixed GWP and GTP for the 4 time-horizons. The categories are ordered according to increasing magnitude in difference, which coincides with increasing spread between the two metrics.

Because CO_2 is the reference gas, the more CO_2 in the mix the smaller the difference between the fixed GWP and fixed GTP. For the first 3 categories, where the non-CO_2 contribution is on the order of 1% or less, differences are small. In such cases, the differences may disappear relative to errors in emission inventories. As the contribution of CO_2 decreases, we expect the difference to increase. This is seen in the next 3 categories, where non-CO_2 GHGs are now the main GHGs in the mixture. But the difference only increases when the CH_4 is the main contributor in the non-CO_2 portion of the mix. In the last 3 categories, the difference can be seen to increase as the proportion of N_2O decreases. The ratio of GWP to GTP for CH_4 peaks at a high value of almost 7 for time-horizon of 91. This high ratio is particularly evident when comparing GWP-100 to GTP-100, for the time-horizon is close to the time-horizon at which the CH_4 ratio peaks. The contribution of N_2O offsets the difference increase caused by CH_4, since N_2O GWP and GTP multipliers are close in value.

Table 33 - Summary of comparison of fixed GWP vs. fixed GTP, and of var GWP vs. var GTP

Emission contributions	**Percentage difference between fixed GWP and fixed GTP as a function of TH**	**As TH increases, percentage difference:**	**Sector examples**
Mostly CO_2, CH_4 and N_2O in order of 0.01%	Insignificant <2%	Increases	Industrial processes, fuel combustion for 2010
Mostly CO_2, CH_4 and N_2O in order of 0.1%	Very small 2-7%	Increases up to TH=50, then decreases	Fuel combustion all period, land-use
Mostly CO_2, CH_4 and N_2O in order of 1%	Small 8-30%	Increases up to TH=50, then decreases	Fugitive, all sector
CH_4 in order of 90%, N_2O order of 10%	Medium 10-70%	Increases	Charcoal
CH_4 in order of 95%, N_2O order of 5%	Large 20-170%	Increases	Agriculture and livestock
CH_4 in order of 95%, N_2O order of 1%	Very large 20-370%	Increases	Waste

Notes: The contribution ranges are approximations.

As was pointed out in Section 5.2, emission accounting for CO_2-intensive sectors can have errors of approximately 10%, while CH_4-intensive sectors such as agriculture and livestock and waste can have errors of approximately up to 50%. It is not straightforward to determine the effect of these uncertainties on the comparisons, unless the over- or underestimations are the same for both CH_4 and N_2O, for these are multi-gas mixes, which means that emission errors may offset or reinforce each other in the total mix. As an example, if CH_4 emissions in the agriculture and livestock sector were underestimated by 50% and N_2O overestimated by 50%, a re-calculation of the fixed GWP and GTP for the correct value leads to a fixed GWP to fixed GTP percentage difference range of 13% (for 2020) to 77% (for 2100), as opposed to the previous 19% to 170% listed in Table 33. If CH_4 is overestimated and N_2O underestimated by the same amounts, the range becomes 21% to 311%.

The analysis of the variability between the use of fixed metrics GWP and GTP shows the importance of correct emission accounting and of awareness in the consequences of the choice of metrics in CH_4-intensive sectors, exemplified here by charcoal production, agriculture and waste treatment. These results should be taken into account for developing countries where CH_4 intensive sectors are highly relevant sectors. Of the sectors studied, the waste treatment sector, where N_2O contributes the least and CH_4 the most, is the most sensitive to metric variability, and is precisely one of the sectors in Brazil where there is still much uncertainty in the data collected.

7.5.2. Variable GWP versus variable GTP

For an individual GHG, we need to compare:

$$\left[\sum_{t=t_i}^{t=t_f} E_x(t)\,.\,GWP_x(T-t)\right] \; versus \; \left[\sum_{t=t_i}^{t=t_f} E_x(t)\,.\,GTP_x(T-t)\right]$$ **Equation 41**

For a multi-gas mix, we compare:

$$\sum_x \left[\sum_{t=t_i}^{t=t_f} E_x(t)\,.\,GWP_x(T-t)\right] versus \sum_x \left[\sum_{t=t_i}^{t=t_f} E_x(t)\,.\,GTP_x(T-t)\right]$$ **Equation 42**

For one individual GHG, the main determinant of variability is the range of the metric functions from where the metric multipliers are taken, which depends on the impact year relative to when the period occurs, and the length of the period of the emission series. For variable metric impact in 2100, for instance, the 41-year period 1970-2010 determines the time-horizon interval to be between 90 to 130, so that the discount multipliers to be compared are GWP-90 to GWP-130 and GTP-90 to GTP-130.

For one individual GHG, while for comparison of the fixed metrics it was sufficient to compare the ratio between the GWP and GTP values at a fixed time-horizon, since one single multiplier weighs an aggregate pulse independently of the individual emission pulses, here we must weigh the individual emission pulses by metric values selected from an entire time-horizon interval.

For the multi-gas scenarios, the percentage differences between the variable metrics are similar to the differences between the fixed metrics, analyzed in the previous section. The similarity in the trends can be confirmed by looking at the percentages shown in the right-hand side of each diagram of Section 6.3 and observing that they are close to the values on the left-hand side. The reasons for the variability trends, as described in the previous sections, are similar. The reason for this similarity is that although the multipliers for the variable case are now taken from an entire time-horizon interval, this latter interval is still a window around the one multiplier used in the fixed case. Because of these similarities, the sectoral analysis conducted in the previous section also applies here and will therefore not be repeated. Table 33 applies for both the comparison of fixed GWP to fixed GTP and to the comparison of variable GWP to variable GTP.

Yet in spite of the similarities, there are some differences between the variabilities in the two cases, and these are investigated below.

For an individual GHG, we can estimate a first-order difference, a *ceteris paribus* case, between the variable GWP and GTP by assuming that the emission pulses are constant, as in this special case the emission pulse can then be factored out from the sum in Equation 41:

$$E_x(t) \,.\left[\sum_{t=t_i}^{t=t_f} GWP_x(T-t)\right] \quad versus \quad E_x(t) \,.\left[\sum_{t=t_i}^{t=t_f} GTP_x(T-t)\right]$$ **Equation 43**

The difference between the variable GWP and GTP is then given by the difference between the sums of the two metrics in the time-lag interval. These metric sums and the ratios between the sums were calculated for the BEB series period 1970-2010, for CH_4 and N_2O.

Table 34- Ratios of variable GWP to variable GTP for time-horizons 20, 35, 50 and 100, for 1970-2010 period.

	Time-horizon	Range of TH	var GWP	var GTP	var GWP/ var GTP	fixed GWP/ fixed GTP
CH_4	100	90-130	977.35	153.70	6.36	6.60
	50	40-80	1,573.60	402.50	3.91	3.34
	35	25-65	1,956.20	829.15	2.36	1.93
	20	10-50	2,569.00	1,726.40	1.49	1.23
N_2O	100	90-130	12,081.00	10,386.00	1.16	1.12
	50	40-80	12,621.00	12,848.00	0.98	0.95
	35	25-65	12,509.00	13,092.00	0.96	0.94
	20	10-50	12,126.00	12,738.00	0.95	0.96

The last column corresponds to Table 26 – Ratio of GWP to GTP for CH4 and N2O, for 4 time-horizons and was included for comparison.

For the same reasons as for the fixed metrics, for CH_4 variable GWP is always larger than variable GTP, and the difference increases as the impact year becomes more distant. For N_2O, the difference is largest in 2100, and the difference is insignificant at closer impact years, where the GWP and GTP values for N_2O are similar.

Of most interest here, still in the *ceteris paribus* case, is the fact that for CH_4 the ratios between the variable metrics are larger than the ratios for the fixed metrics only for the closer time-horizons, as can be seen from comparing the last 2 columns of Table 34, with differences in the order of 15%, which can be significant for CH_4 intensive sectors. For impact year 2100, the trend is inversed, with a smaller variable GWP to GTP ratio compared to the fixed metrics case, because at more distant time-horizons the difference between the GWP and GTP values decreases, as they both asymptotically tend to 0. In other words, in the 'window' of GWP and GTP values used in the variable metrics, there is less of a difference between GWP and GTP at more distant time-horizons. But this difference between the ratios is less than 5%, so the choice between using GWP or GTP, and the choice of time-horizon, are more relevant than the choice between variable versus fixed metrics.

Let us now leave the *ceteris paribus* case. How do the actual ratios, calculated from the actual emission series, compare to the constant-emission special case ratios? These ratios shed light on the effect of the individual pulses of the emission series, over the entire period, on the variability of the variable GWP to GTP ratios. This is shown in the following table for CH_4 emissions from the BEB series. Note that these ratios are not for the multi-gas CO_2-equivalent of the sectors, but just for CH_4.

Table 35 Ratio of var GWP to var GTP for CH_4, by sector and time-horizon.

Time-horizon	Constant pulses	BEB fuel combustion	BEB charcoal	Fugitive	Industrial processes	Agriculture and livestock	Land-use	Waste	All sector
20	1.49	1.44	1.31	1.27	1.27	1.28	1.27	1.28	1.28
35	2.36	2.28	2.10	1.99	2.00	2.03	2.01	2.02	2.03
50	3.91	3.81	3.61	3.43	3.45	3.50	3.46	3.49	3.49
100	6.36	6.40	6.53	6.56	6.56	6.55	6.56	6.55	6.55

We observe here that for smaller time-horizons, for all sectors the ratios are smaller than in the *ceteris paribus* case. This can be explained as follows. In general, if the emission series is increasing, the larger emission pulses at the end of the period will be weighed by the larger metric values at the beginning of the time-horizon interval, in a 'reinforcement ' trend. Since GTP values are closer to GWP values for small time-horizons, the GTP reinforcement in the denominator weighs more than the GWP reinforcement in the numerator of the ratio, decreasing the overall ratio in an 'attenuation' trend. In other words, the ratio of variable GWP to variable GTP is closer to unity if we weigh more heavily the values of the metric function which are more similar. For time-horizon 100, the ratios are all larger, as the GTP reinforcement loses weight.

What is the effect of these results on the multi-gas CO_2-equivalent? If the mixture of gases includes an increasing CH_4 emission series, which has a high GWP reinforcement trend at small time-horizons, because of the difference between GWP and GTP values, the CO_2-equivalent rate of change will be dominated by the CH_4 rate of change.

The CH_4-intensive charcoal sector is analyzed in detail as an illustration of these trends. The emissions are mainly CH_4 (88% CH_4 and 12% N_2O), and the emission series has local maximums and minima, illustrating the rate of change differences. We choose a time-horizon at 2100, where the difference between the metrics is larger and trends easier to identify in a plot.

Figure 33 shows the CH_4 GWP and GTP values used to calculate the variable GWP and GTP metrics for a time-horizon at 2100 plotted according to the right-hand axis values. At the year 1970, for instance, GPW (130) and GTP (130) are plotted. These are the values used to weigh the charcoal sector's CH_4 emissions in year 1970. CH_4 emissions are plotted on the left-hand axis. The emission increase in the 1970-1988 period and the decrease in the 1988-1998 period are seen to become more accentuated in the GWP-based CO_2-equivalent than in the GTP-based CO_2-equivalent as a result of the faster decreasing GWP function. The pulses closer to the time-horizon will therefore be more heavily weighted by the GWP metric than the GTP metric. The ratio of the var-GWP to var-GTP metric ranges from 5.88 in 1970 to 6.68 in 2010 and averages out to 6.35, very close to the ratio for a constant annual pulse.

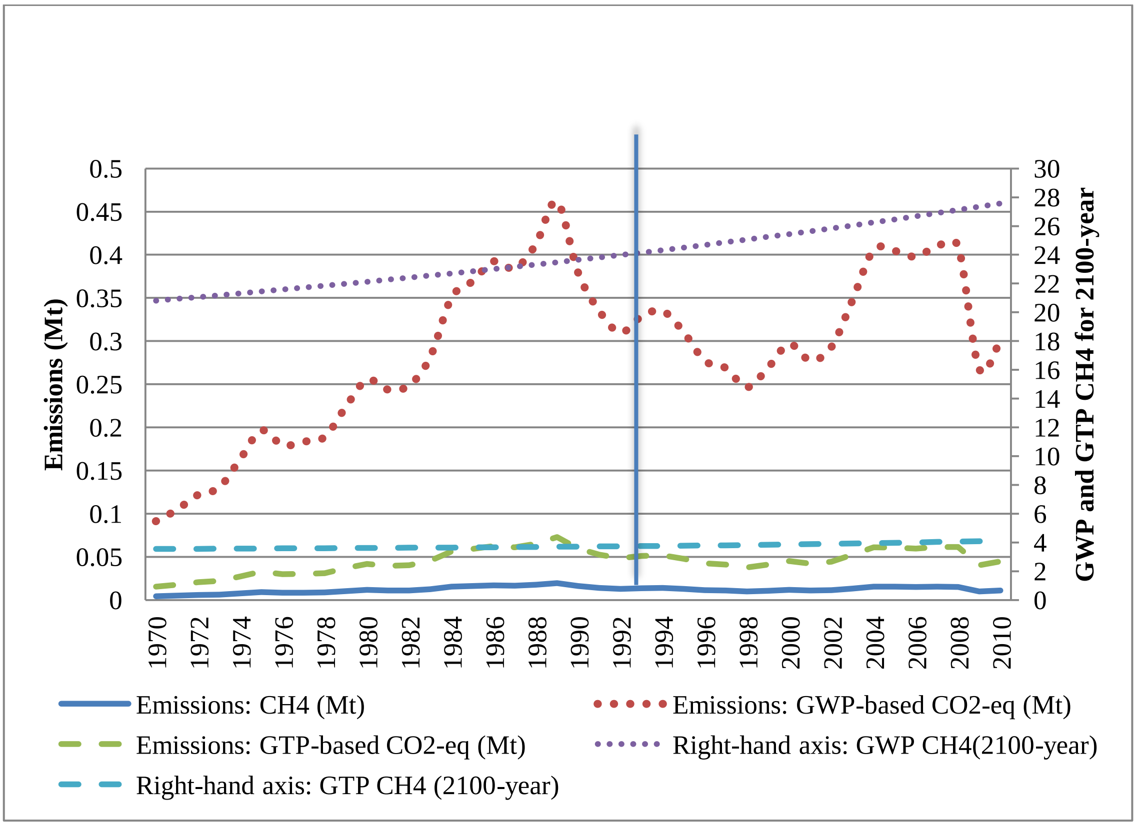


Figure 33 - Charcoal sector CH_4 emissions and variable GWP and GTP-based CO_2-equivalent..

7.5.3. Fixed GWP versus variable GWP

For an individual gas, we compare a value consisting of a sum of a series emission pulses discounted by one fixed GWP multiplier dependent on the time-horizon, with the same pulses discounted independently by multipliers dependent on the distance of each pulse to the impact year.

$$\left[\sum_{t=t_i}^{t=t_f} E_x(t)\right].GWP_x(TH) \;\; versus \;\; \left[\sum_{t=t_i}^{t=t_f} E_x(t).GWP_x(T-t)\right]$$ **Equation 44**

Consider an emission series with a period of $\Delta t = t_f$-t_i years, for year of impact *T*. For the fixed metric, the time-horizon is *TH* = *T-2000*, and the sum of the pulses is discounted by one single multiplier GWP-TH. For the variable case, the pulses are discounted by multipliers which span a window of Δt years, ranging from GWP-(*T-ti*) to GWP-(T-t_f). A relevant feature of this comparison is that the value GWP-TH used for the fixed metric is within this range, so since the GWP and GTP are continuous, the fixed metric multiplier is always close in value to the multiplier used for the variable metric. For instance, for the 1970-2010 BEB series, we have Δt = 41. For impact year 2020, we have TH = 20 and a multiplier range between GWP-10 and GWP-50. For impact year 2100, we have TH=100 and a multiplier range between GWP-90 and GWP-130. This fact explains why the difference between the metrics is always small, as will be seen below.

In an attempt to identify general trends for one GHG, we consider again the special case of constant pulses for the BEB series (1970-2010), in which case we can factor out the emission pulses from the weighted sum given in Equation 32. We can then compare the sum of the variable GWP multipliers for a specific period with the fixed multiplier, weighted by the number of pulses in the series. For the case of 41 constant pulses, we compare:

$$[41. E_x(t). GWP_x(TH)] \ \ versus \ \ E_x(t) \, . \left[\sum_{t=t_i}^{t=t_f} GWP_x(T-t) \right]$$

Equation 45

which is equivalent to:

$$[41. GWP_x(TH)] \ \ versus \left[\sum_{t=t_i}^{t=t_f} GWP_x(T-t) \right]$$

Equation 46

It can be shown that combinations of periods and impact years exist for which the variable GWP is larger than the fixed GWP, or the other way around. For instance, for CH_4, for impact year 2100, for 41 pulses between 1970 and 2010, the fixed GWP is larger. But for 29 pulses between 2020 and 2048, the variable GWP is larger (Moura et al., 2012).

Table 36 – Comparing fixed and variable GWP for CH_4 for time-horizon 100: two examples.

	29 pulses (2020-2048) TH range: 52 to 80	41 pulses (1970-2010) TH range: 90 to 130
Fixed GWP-100	29*25.44=737.76	41*25.44=1043.04
Var. GWP 2100	1022.7	977.35
Fix GWP/var GWP	0.72	1.07

If the multipliers are drawn from a section of the GWP function where values are high, even if there are few pulses in the period, the variable sum can be larger than for a case in which they are drawn from a section where the GWP values are smaller and there are more pulses.

For our specific case of a 1970-2010 period with constant pulses, fixed GWP is larger than variable GWP by small margins, but if the fixed GWP are discounted by the NRIs, the percentages are reduced and the difference between the metrics is insignificant. For N_2O, the differences are insignificant because of the small slope of the N_2O function in the vicinity of the time-horizons considered.

Table 37 – Ratios fixed GWP/variable GWP for constant pulses, for 41-year BEB series, for 4 time-horizons.

	Time-horizon	Range of TH	Var. GWP	41.fix GWP	fix GWP/ var. GWP
CH4	100	90-130	977.35	1043.04	1.07
	50	40-80	1,573.60	1756.03	1.12
	35	25-65	1,956.20	2234.50	1.14
	20	10-50	2,569.00	3022.11	1.18
N_2O	100	90-130	12,081.00	12,263.06	1.02
	50	40-80	12,621.00	12,637.71	1.00
	35	25-65	12,509.00	12,399.29	0.99
	20	10-50	12,126.00	11,822.93	0.98

Now looking at the actual multi-gas emission series, rather than the constant pulse case, for both the BEB series (1970-2010) and the MCT series (1990-2005), the differences between the fixed and variable GWP correspond to the top percentage shown in each individual diagram in Section 6.3. Fixed GWP is larger than the variable GWP for all sectors, for CH_4 as well as for the total CO_2-equivalency. For the fugitive emissions sector for the short MCT period (1990-2010), this trend is reversed. For all scenarios studied here, the percentage differences decrease as the impact year becomes more distant, as the slope of the section of the GWP function from which the multipliers are drawn decreases.

For the BEB series, for the entire period and all sectors (Scenario 1A, Case 1), the difference decreases but is insignificant (less than 2%). For just the charcoal sector

(Case 2), the differences vary from about 8% to 3% as the impact year becomes more distant. For the MCT II scenarios, all differences are small, the largest being around 3.5% in 2020 for the waste sector and the agriculture sector. The GWP multipliers for the variable case are taken from an entire time-horizon interval, but this interval is still a window around the one multiplier used in the fixed case, as explained above. Unlike the comparison between GWP and GTP, for which there are significant differences when CH_4 is the major contributor, here the differences are therefore insignificant.

In the comparison between fixed and variable metrics for the same metric, the proportion of GHGs in the mix is not as important as they are in the comparison between GWP and GTP, as we are comparing the same metric (here GWP). This explains why the difference for the waste sector may be smaller than that for the charcoal sector, which is not the case for the comparisons between GWP and GTP (see Table 33) , even though the waste sector has a higher contribution of CH_4.

The main reason the variable GWP value for the charcoal sector is further apart from the waste sector is due to the different periods being considered. For the BEB series, the window of multipliers spans 41 years, while for the MCT series it spans 16 years. For the waste sector emissions, derived from the MCT data, the GWP multipliers are taken from a range with larger values, as the first 20 years between 1970 and 1990 are not included (these excluded years span the range GWP-130 to GWP-110, respectively, which are smaller values). As an example, for 2020, the range of multipliers for the 41-year BEB series is GWP-10=92.9 to GWP-50=42.8 , while for the 16-year MCT series the range is GWP-15=82.6 to GWP-30=59.8, which leads to a higher average per pulse.

The variation between the metrics is also determined by the shape of the emission series, which weighs the multipliers and leads to attenuations or offsets in the variable case, as explained in the previous section. The slightly larger difference for the charcoal sector (8.2% for 2020) as opposed to the waste sector (3.5% for 2020) can also be explained by this effect.

These results indicate that the choice between GWP or GTP is more important than the choice between fixed and variable versions of the metrics. This confirms the results obtained in the two previous sections, when we compared fixed GWP with fixed GTP (Section 7.5.1), and variable GWP with variable GTP (Section 7.5.2), and concluded that that the choice between GWP and GTP leads to greater variability than the choice between fixed and variable metrics.

7.5.4. Fixed GTP versus variable GTP

The comparison here is very similar to the one in the previous sections.

For an individual gas, we compare a value consisting of a sum of a series emission pulses discounted by one fixed GTP multiplier dependent on the time-horizon, with the same pulses discounted independently by multipliers dependent on the distance of each pulse to the impact year, as was the case with GWP.

$$\left[\sum_{t=t_i}^{t=t_f} E_x(t)\right].GTP_x(TH)\ \ versus\ \ \left[\sum_{t=t_i}^{t=t_f} E_x(t).GTP_x(T-t)\right] \quad \textbf{Equation 47}$$

The case of constant pulses for the BEB series (1970-2010), where the formulation is equivalent to the one described in the previous section and results are summarized in the following table, equivalent to Table 37. For CH_4, as before, fixed GTP is larger than GTP for all time-horizons, but the differences are larger (1.03 to 1.42 for GTP, and 1.07 to 1.18 for GWP). The reason for this, say for 2020, is that the difference of sum of the GTP values in the GTP-10 to GTP-50 interval and the equivalent sum for GWP is larger than the difference between the fixed values GTP-20 and GWP-20. In other words, the ratio of the integrals in the 20 to 50 time-horizon range is larger than the ratio of the values at one point on the GWP and GTP functions. The underlying cause of this is more rapidly decreasing GTP function.

For very close time-horizons, the contribution of CH_4 should therefore be taken into account when choosing between the fixed GTP and variable GTP, as metric differences for constant pulses can be in the order of 30-40%.

Table 38– Ratios fixed GTP/variable GTP for constant pulses, for 41-year BEB series, for 4 time-horizons.

	Time-horizon	Range of TH	var GTP	41.fix GTP	Fix GTP/ var GTP
CH4	100	90-130	153.70	158.12	1.03
	50	40-80	402.50	524.21	1.30
	35	25-65	829.15	1159.19	1.40
	20	10-50	1,726.42	2458.70	1.42
N_2O	100	90-130	10,385.69	10911.49	1.05
	50	40-80	12,847.92	13236.48	1.03
	35	25-65	13,091.99	13173.23	1.01
	20	10-50	12,738.17	12338.10	0.97

For the multi-gas comparison, the same trends apply to the comparison between the fixed and variable versions of GTP as apply to the comparison in the previous section, for GWP. The difference between this comparison and the previous one is due only to the difference between the GWP and GTP functions for each GHG. Here the percentages relating to a comparison of the multi-gas case are shown in the bottom of each individual diagram in Section 6.3.

As before, fixed GWP is larger than the variable GWP for all sectors, for CH_4 as well as for the total CO_2-equivalency (with the exception of the fugitive emissions sector for the short MCT period 1990-2010).

Looking at the charcoal sector, as was seen in the previous section, for the fixed GWP with the variable GWP, the difference decreases from 8.2% for 2020, to 6.0% for 2035, to 4.7% for 2050 to 2.9% for 2100. Comparing now the fixed GTP with the variable GTP, the difference decreases from 16.5% for 2020, to 11.0% for 2035, to 6.8% for 2050 to 4.0% for 2100. The decreasing difference reflects the fact that, for CH_4, as the time-horizon is further away from the moment of emission, both GWP and GTP values decrease steadily. The larger GTP range reflects the fact the GTP values decrease faster than GWP values as the time-horizon is further away. Higher GTP percentage differences reflects both the fact that CH_4 GWP values are larger than the CH_4 GTP values as well as the fact that GTP decreases faster. When comparing the charcoal and

For the waste sector, the difference decreases from 7.6% for 2020 to 0.8% for 2100. The absence of the first 20 years (1970-1989) from the MCT series removes precisely the smallest metric values, where there is more similarity between the multiplier values (at smaller time-horizons, the GWP/GTP ratio is smaller, as can be seen from Figure 31), so the heavier weight of CH_4 in this sector relative to the charcoal sector, is offset by a set of smaller multiplier values.

Results indicate that more care should be applied to the choice between fixed and variable GTP than to the choice between fixed and variable GWP. Differences for constant pulses can be up to 42%, which indicates that for certain emission series this choice could be relevant. Still, for all sectors analyzed here, the multi-gas comparison maximum difference was 16% for the CH_4-intensive charcoal sector for a very close time-horizon of 2020.

7.6. Comparison between time-horizons for the same metric

The variation between the CO_2-equivalent emissions for time-horizons 2020, 2035 and 2050 relative to 2100 was calculated for each metric, for the Second Inventory emission scenarios described in section 6.2.

The variations are calculated according to the following equations:

$$\frac{fix\ GWP(TH) - fix\ GWP\ (100)}{fix\ GWP(100)} * 100\%$$

Equation 48

$$\frac{fix\ GTP(TH) - fix\ GTP\ (100)}{fix\ GTP(100)} * 100\%$$

Equation 49

The tables below show the variations.

Table 39 – Variation based on time-horizon 2020 and 2100 between CO_2-eq emissions for same metric, for MCT II emission scenarios

	Energy	Fugitive	Industrial processes	Agricultire and Livestock	Land-use and forestry	Waste treatment	All sectors
Fix GWP-20 vs. fix GWP-100	5.5%	42.7%	0.3%	132.2%	11.0%	173.6%	37.0%
Var GWP-2020 vs. var GWP-2100	5.2%	41.3%	0.3%	127.2%	10.6%	167.7%	35.4%
Fix GTP-20 vs. fix GTP-100	6.7%	61.4%	1.6%	426.2%	13.6%	950.9%	53.4%
Var GTP-2020 vs. var GTP-2100	6.1%	57.8%	1.7%	396.2%	12.7%	884.1%	49.3%

Table 40– Variation based on time-horizon 2035 and 2100 between CO_2-eq emissions for same metric, for MCT II emission scenarios

	Energy	Fugitive	Industrial processes	Agricultire and Livestock	Land-use and forestry	Waste treatment	All sectors
Fix GWP-35 vs. fix GWP-100	3.3%	25.7%	0.4%	80.5%	6.7%	104.8%	22.5%
Var GWP-2035 vs. var GWP-2100	3.2%	25.0%	0.5%	77.9%	6.4%	101.7%	21.6%
Fix GTP-35 vs. fix GTP-100	3.1%	26.7%	1.8%	196.2%	6.0%	418.9%	24.3%
Var GTP-2035 vs. var GTP-2100	2.8%	25.2%	1.9%	181.9%	5.6%	386.9%	22.4%

Table 41– Variation based on time-horizon 2050 and 2100 between CO_2-eq emissions for same metric, for MCT II emission scenarios

	Energy	Fugitive	Industrial processes	Agricultire and Livestock	Land-use and forestry	Waste treatment	All sectors
Fix GWP-50 vs. fix GWP-100	2.0%	15.4%	0.5%	48.9%	4.0%	62.9%	13.6%
Var GWP-2050 vs. var GWP-2100	1.9%	15.0%	0.5%	47.6%	3.9%	61.3%	13.2%
Fix GTP-50 vs. fix GTP-100	1.3%	9.8%	1.7%	81.5%	2.2%	157.9%	9.9%
Var GTP-2050 vs. var GTP-2100	1.2%	9.3%	1.7%	76.3%	2.1%	146.0%	9.2%

Results show that in sectors with a high contribution of CH_4 in the total mix, on the order of 95%, the variation due to time-horizon for the same metric can be more significant than the variation between different metrics for the same horizon. The variations for GTP are larger than for GWP, given the GTP function decreases faster than the GWP function (see Section 7.1). For the waste treatment sector and the agriculture and livestock sector, the variations are the largest, as they are CH_4-intensive sectors: emissions based on GTP-20 values are on the order of 10 times emissions those based on GTP-100, on the order of 5 times for emissions based on GTP-35 and 2.5 times for emissions based on GTP-50 (the variations are 950%, 419% and 158%, respectively). For fugitive emissions, the variation for GTP ranges from approximately 60% to 10% . For the sectors which emit mostly CO_2, such as the energy, industrial processes and the land-use and forestry sectors, the differences are less than 10%.

8. Implications for policymaking and conclusion

An increased awareness concerning the quantitative accuracy of emission reduction reports, and a clarification concerning the various emission reductions interpretations, are important elements in the consolidation of the credibility of multi-gas equivalency. The degree to which GHG emission mitigation efforts are perceived to be beneficial depends on the methodology used to estimate multi-gas equivalency and on how the emission reductions are reported. Currently, reporting of multi-gas emissions used in policymaking and in international climate change negotiations does not generally address the criteria assumed in analyses and does not take methodological differences sufficiently into account, generally calculating the multi-gas equivalency based on the GWP-100 recommended by the IPCC. Temporal factors, such as the target year for the climate impact and the time-horizon relative to the moment of emissions, are particularly critical. Other issues, such as the need to disaggregate emission pulses and the methodology for discounting the time gap between the emission pulse and the target year, also affect temporal considerations. Policies focused on closer target years are especially vulnerable to the differences between metrics which do and do not account for the time-horizon more accurately, particularly when CH_4 is a relevant GHG. Depending on the emissions profile and the policy goal, it is important to assess and prioritize these factors based on a quantitative assessment, when possible, for these choices may lead to different interpretations and to the formulation of different mitigation strategies (Manne and Richels, 2001). This awareness will also help to identify the key variables that should be addressed to match the targets proposed for GHG mitigation.

Regions, countries and sectors with a significant proportion of CH_4 and N_2O in their emission profiles are particularly prone to distortions in multi-equivalency emissions accounting.

It is instructive to investigate the effect of metric choices on the Brazilian pledge[57], in light of the analysis conducted in this study. In this case, the CO_2-equivalent for certain sectors (to be specified in detail below) are fixed at constant percentages of the total mitigation desired. An inverse analysis must therefore be conducted, relative to the

[57] Announcement made at the 15th Conference of the Parties (COP 15), Copenhagen (UNFCCC, 2010)

analysis conducted in Chapters 6 and 7, where the CO_2-equivalent variability of historical emissions series was determined. Here, as long as the overall sector target is met, we have freedom to choose a metric to determine the emissions from each GHG for each sector. For each metric chosen, the absolute emissions of each GHG will be different. These results are presented in detail in Appendix B.

When emission reduction potentials are presented to policymakers, criteria are presented along with the numbers, justifying the choices made in the calculations that results in those numbers. When multi-gas equivalency metrics are being selected, there are many criteria which can be chosen by analysts presenting a country, region or sector emissions to policymakers. We are assuming here that the policymaker has already chosen to use a physical emission metric, as opposed to a metric which accounts for economic or social factors. Some of the criteria which could be considered are:

- Which mix of GHGs should the policymaker consider? How much effort should be invested in obtaining data about short-term GHGs?
- What time-horizon should the policymaker choose for the moment of impact?
- What kind of impact should the policymaker choose: integrated radiative forcing and therefore the traditional and widely accepted GWP metric, or temperature change and therefore the so-far less common but more relevant end-point GTP metric?
- Should the policymaker aggregate annual emissions or is there a benefit from taking annual emissions into account, if they are available?
- Should the policymaker be concerned about emission characteristics such as the shape or the average of the pulses in the time-series?

These criteria can be selected to ‘skew’ results in a particular direction. Policymakers can choose a certain way of looking at the numbers which make small differences become more or less significant, depending on the purpose of a certain policy.

This study shows that it is possible to have multiple interpretations of the relative contributions to the emission reductions in CO_2-equivalent, depending on the criteria taken into account. The use of percentage reporting in mitigation brings these considerations into focus in policy contexts. These multiple interpretations can be made because approximately constant emission reductions, in CO_2-equivalent, can be compared to a varying emission total, also in CO_2-equivalent.

Following are a set of 4 guidelines for decision-makers, based on the results of this study. First, there is a set of general guidelines, followed by guidelines comparing the fixed metrics with each other, guidelines comparing the variable metrics with each other, and guidelines comparing the fixed versus the variable metrics.

8.1. General guidelines

- Very generally, the factors that may affect the difference between metrics are: the characteristics of the metric functions and their relationship to each other, the relative contribution of the GHGs in the multi-gas mix (particularly the contribution of high-impact gases such as CH_4 and N_2O), the location in time of the emission period relative to the impact year and relative to the year 2000, the length of the emission period, and the shape of the emission pulse. Depending on the specific comparison, some factors will weigh more than others in the comparison. At times factors will reinforce each other, and at times factors will offset each other, in which case it might appear, incorrectly, that two metrics are similar.
- When deciding which metric to use, more variability will be encountered when choosing between GWP and GTP than between the traditional fixed metrics and the metrics which account for the time-lag between annual pulses and the impact year. The choice between GWP and GTP is more significant than the choice between fixed and variable metrics. In other words, when making comparisons between fixed GWP and fixed GTP, and between variable GWP and variable GTP, percentage differences can be significant. Yet these percentage differences are similar in both comparisons, indicating that the more relevant comparison is between GWP and GTP.
- Decision makers should pay particularly close attention to time-horizon. For methane intensive sectors, such as the waste treatment sector, the variation between the CO_2-equivalent, for the same metric, for impact in 2020 relative to 2100, can be much larger than the variation between different metrics for the same time-horizon. For the waste treatment sector, for instance, emissions based on fixed GTP-20 are

approximately 10 times as large as emission based on fixed GTP-100, emissions based on fixed GTP-35 are approximately 5 times as large and emissions based on GTP-50 are 2.5 times as large. The further away the impact year, the more important the choice between GWP and GTP becomes, rather than between fixed versus variable. That is, for a distant impact year, the choice of GWP, whether the fixed or variable version, will emphasize the presence of CH_4 in a multi-gas mix, since the GWP multiplier for the latter gas is 6.6 times the value of the GTP multiplier in 2100. For closer impact years, the choice between fixed versus variable becomes more relevant, particularly for GTP. For a close impact year, for instance, the choice of a fixed metric rather than variable metric will give more weight to the CH_4 contribution in the mix.

- When comparing GWP and GTP, in either their fixed or variable versions, the contributions of CH_4 and N_2O in the multi-gas mix can lead to highly significant variability. When CH_4-intensive sectors are being accounted for in a multi-gas mix or individually, it is especially important to take the difference between GWP and GTP into account. In some sectors, GWP-based CO_2-equivalents might be over 4 times as large as GTP-based vales.
- If the CO_2 contribution relative to CH4 and N2O is large, the overall CO_2-equivalent in any metric masks the dependency of CH4, in CO_2-equivalents, on time-horizon. As an example, for the land-use sector, at impact year 2100, the variable GWP-based CO_2-equivalent is more than six times as large as the variable GTP-based emissions, yet when all GHGs in the sector are accounted for, the difference is 5%.
- When comparing two metrics at a specific impact year and either of them is a fixed metric, the distance of the emission center of mass from the year 2000 should be accounted for in order to avoid over- or under-estimations of the impact at the specified year. The normalized real impact (NRI) indicator is a suggested discount factor which is a function of the GHG, the offset from the year 2000 and the impact year.

8.2. Fixed GWP vs. fixed GTP

- For CH_4, fixed GWP is always larger than fixed GTP, for all time-horizons and all sectors considered here, the difference increasing as the impact year becomes more distant. So choosing variable GWP will give more weight to the presence of CH_4 in the GHG mix, particularly for more distant impact years.

- To have an idea of the degree to which CH_4 or N_2O are weighted based on the choice of fixed GWP or GTP, the fixed ratios for each time-horizon can be used, as given by Figure 24.

- For CH_4, the GWP to GTP ratio is maximum at TH=91, corresponding to an almost seven-fold difference in the metrics.

- For N_2O, a choice between fixed GWP and fixed GTP does not make much of a difference for the time-horizons studies here. If the details are looked into anyway, for further impact year 2100 the fixed GWP is larger than the fixed GTP, as for CH_4, but this does not hold true for closer impact years because of the peak in the N_2O metrics functions. For very distant impact years, beyond 2150, however, there is a significant difference between GWP and GTP values, which will not be addressed here.

- For CO_2-equivalents for all 3 GHGs, fixed GWP is always larger than fixed GTP, for all time-horizons. If the approximate contribution of GHG emissions is known, Table 33 can be used for guidelines for the total CO_2-equivalent variability between a fixed GWP or fixed GTP choice.

- Even small contributions of CH_4 and N_2O in the multi-gas mix can have noticeable effects on the difference between the metrics. A 0.1% absolute contribution has little effect (fuel combustion, land-use), yet a 1% contribution (fugitive sector, all sectors of the economy) may lead up to a 30% difference.

CH_4 intensive sectors are subject to large differences (up to 70% for charcoal, 170% for agriculture and livestock, and 370% for waste sector).

8.3. Var GWP vs. var GTP

- For CH_4, variable GWP is always larger than variable GTP, for all time-horizons and all sectors , the difference increasing as the impact year becomes more distant. So choosing variable GWP will give more weight to the presence of CH_4 in the

GHG mix, particularly for more distant impact years. This is the same result as in the comparison between the fixed metrics, because variable metric values in this case are drawn from an interval of values in the proximity of the fixed value.

- To have an idea of the degree to which CH_4 or N_2O are emphasized based on the choice of variable GWP or GTP, without having to analyze the actual emission values series, the ratios for the case of constant pulses can be used as a guideline. However, the time interval of the emission series will have to be known, for these ratios are independent of the value of the pulses but dependent on the emission period.

- The special case of constant pulses for both the fixed comparison and the variable comparison indicates clearly that the choice between GWP and GTP is more relevant for the decision-maker than the choice between variable and fixed metrics.

- For impact years further away, such as 2100, the difference between variable GWP and variable GTP for CH_4 for the constant emissions case and the actual emissions is on the order of 5%, which is insignificant. For close impact years, the difference for the actual emission will be on the order of 15%, which might or might not be significant, depending on the application and other uncertainties (the actual ratios are 15% smaller then the constant pulse guideline ratios).

- For N_2O, a choice between variable GWP and variable GTP does not make much of a difference for the time-horizons studies here. If the details are looked into anyway, for further impact year 2100 the variable GWP is larger than the variable GTP, as for CH_4, but this does not hold true for closer impact years because of the peak in the N_2O metrics functions. For very distant impact years, beyond 2150, however, there is a significant difference between GWP and GTP values, which will not be addressed here.

- For CO_2-equivalents for all 3 GHGs, variable GWP is always larger than variable GTP, for all time-horizons. If the approximate contribution of GHG emissions is known, Table 33 can be used for guidelines for the total CO_2-equivalent variability between a variable GWP or variable GTP choice.

- As in the fixed GWP to fixed GTP comparison, particular attention should be paid to the contribution of CH_4 in the multi-gas mix (see previous table).

8.4. Fix GWP vs. var GWP and fix GTP vs. var GTP

- These comparisons confirm that the choice between GWP and GTP is generally more important than the choice between fixed and variable metrics. For GTP, larger differences of up to 42% were calculated for constant pulses, but for actual emissions from the sectors, differences in the order of 16% for a very close time-horizon are insignificant compared to the largest differences, in the order of 350%, obtained for the GWP-GTP comparisons.

- For an individual gas, it is not possible to generalize about the relative values of fixed GWP and variable GWP, or between fixed GTP and variable GTP. This depends on the emission series values and period. Results, however, indicate a tendency for fixed GWP to be larger than variable GWP, and for fixed GTP to be larger than variable GTP: this is true for all sectors considered, except the fugitive emissions sector, due to characteristics of the emission series values.

- For constant pulses, the difference in metric for an individual GHG is given by the difference between the fixed metric at an impact year and the sum of the multipliers drawn from the metric function interval defined by the period. The ratios corresponding to these differences depend only on the period and the time-horizon, and do not depend on the emission pulses, and can be provided as guidelines.

- Differences are insignificant for all sectors, with the possible exception of the charcoal sector, where differences are around 8% for GWP and 16% for GTP for the closest time-horizon of 2020. The main reason for this is that we are comparing the fixed and variable versions of the same metric, and metric value used in the fixed case is drawn from within the interval of the variable case.

- Variability in the differences are also determined by the shape of the GHG emission pulses and their contributions in the mix, although these factors are not significant relative to the fact that we are comparing temporally distinct versions of the same metric.

9. Suggestions for further studies

The methodology developed in this study can be applied to scenarios including a larger range of GHGs, particularly GHGs with high impact factors. This study demonstrates that even small amounts of high-GWP gases can affect multi-gas equivalency. Furthermore, some substances cause cooling effects and others cause warming, so a more comprehensive study should include a larger range of substances, including the oxides of nitrogen (NO_x), black carbon (BC), CO and VOC and other greenhouse gases. For the case of Brazil, even though the absolute contribution of some of these GHGs is small, the study could be expanded by including the Second Inventory emissions data for HFC's (HFC-23, HFC-125, HFC-134a, HFC-143a, HFC-152a) and for CF_4, C_2F_6 and SF_6, as well as for CO, NO_x and NMVOCs.

Still concerning Brazil, further studies could investigate the role of the choice of metrics in assessing emissions resulting from the increased fossil-fuel based energy consumption, in the context of diminishing Brazilian hydroelectric potential and increased use of natural gas and coal in thermoelectric power plants. At a sectoral level studies using the database developed in this study[58] could be conducted to answer questions such as: How does the choice of metric affect the apparent impact of future changes in land-use and forestry, or the impact of a changing transportation fuel matrix?

Life-cycle analysis scenarios which include short-lived gases such as CH_4 and N_2O should also take into account the effect of metrics on the equivalent emissions. LCAs have generally used GWP-100 and have typically not considered the implications of temporal considerations. One such study has already been conducted (Moura et al., 2012), namely the implications of the choice of time-horizon for the fixed and variable GWP metric in the LCA of a Brazilian coal-based thermoelectric power plant using CCS, with interesting results. The emissions reduction of CCS is 90%, if the plant is considered the boundary of the process, and if one looks only at CO_2 emissions. Yet when other criteria are incrementally included in the analysis, ranging from the inclusion of the energy penalty, the inclusion of other GHGs CH_4 and N_2O, the choice of fixed or variable GWP, and the time-horizon, the benefit is reduced from 90% to 52%. The field of biofuels, for which there have been studies investigating the effect of

[58] This database must first be updated, based on the new official update for the Second Inventory, recently published and not available when this study was conducted.

time-dependent conditions (Kendall et al., 2009; O'Hare et al., 2009b; Cherubini et al., 2011; Peters et al., 2011) could be furthered by including the effect of using GTP rather than GWP.

At a broader level, results from this study can be used to determine how developmental pathways for different countries are affected by the choice of metric. Future scenarios which take into account emission contributions from different economic sectors, or from different technologies, should be investigated from the perspective of a broader set of metrics. How metric-dependent are developmental pathways established for a country? Climate impact studies using the 'wedge approach', pioneered by Pacala (2004), could be expanded to investigate the effect of metric choice. One question which could be answered is: How much margin is there in a pathway, given the variability of the underlying metrics used?

As climate change impacts intensify, mitigation efforts may need to become more concerned with the short-term effects of emissions. How much emphasis should be given to mitigation strategies for short-lived GHGs and high-impact long-lived GHGs such as CH4 and N2O, compared to long-lived GHGs? How are mitigation abatement cost curves affected by the use of different metrics?

If policymakers wish to assign emission wedges to the countries based on emission responsibility, how is this metric-dependent impact variability to be dealt with? What are the implication to pledges of the BASICs or BRICs? The growth forecasts of emerging developing countries such as China and India bring to the forefront the issue of responsibility for national emissions. How does the use of a temperature-based metric such as GTP affect the emission forecasts of these countries? How can the choice of metrics influence the discussion of sharing emission burden, and in what circumstances could it benefit countries that are still building their economic infra-structures? How can the choice of metric impact the results of efforts already undertaken to reduce GHG emissions, such as the Kyoto Protocol?

Since this study was started, the awareness of the importance of emission metric frameworks and metric choices has been steadily increasing in the scientific community (Aamaas et al., 2012; Deuber et al., 2013; Tanaka et al., 2013). Hopefully, as a result of this increased awareness, more accurate assessments of emission impacts and stabilization targets will be developed, leading to the development of more effective mitigation strategies in both national and international contexts.

References

Aaheim, H.A., Fuglestvedt, J.S., Godal, O., 2006. Costs Savings of a Flexible Multi-Gas Climate Policy. The Energy Journal Special Issue #3, 485–502.

Aamaas, B., Peters, G.P., Fuglestvedt, J.S., 2012. A synthesis of climate-based emission metrics with applications. Earth System Dynamics Discussions 3, 871–934.

Achard, F., 2004. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles 18.

Aguiar, A.P.D., Ometto, J.P., Nobre, C., Lapola, D.M., Almeida, C., Vieira, I.C., Soares, J.V., Alvala, R., Saatchi, S., Valeriano, D., Castilla-Rubio, J.C., 2012. Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: the INPE-EM framework applied to the Brazilian Amazon. Global Change Biology n/a–n/a.

Andres, R.J., Fielding, D.J., Marland, G., Boden, T.A., Kumar, N., Kearney, A.T., 1999. Carbon dioxide emissions from fossil-fuel use, 1751-1950. Tellus B 51, 759–765.

ANEEL, 2013. Agência Nacional de Energua Elétrica.

BEN, 2011. Balanço Energético Nacional.

Berntsen, T., Fuglestvedt, J., 2008. Global temperature responses to current emissions from the transport sectors. Proceedings of the National Academy of Sciences 105, 19154–19159.

Boden, T.A., Marland, G., Andres, R.J., 1995. Estimates of global, regional, and national annual CO2 emissions from fossil-fuel burning, hydraulic cement production, and gas flaring: 1950-1992.

Boitier, B., 2012. CO2 emissions production-based accounting vs consumption: Insights from the WIOD databases. WIOD Final Conference - Causes and Consequences of Globalization, Groningen, 24th-26th April, 2012.

Bond, T.C., Sun, H., 2005. Can Reducing Black Carbon Emissions Counteract Global Warming? Environ. Sci. Technol. 39, 5921–5926.

Boucher, O., Friedlingstein, P., Collins, B., Shine, K.P., 2009. The indirect global warming potential and global temperature change potential due to methane oxidation. Environmental Research Letters 4, 044007.

Boucher, O., Reddy, M.S., 2008. Climate trade-off between black carbon and carbon dioxide emissions. Energy Policy 36, 193–200.

Bradford, D.F., 2001. Global change: Time, money and tradeoffs. Nature 410, 649–650.

BSI, 2013. PAS 2050 Assessing the life cycle greenhousse gas emissions of goods and services.

CDIAC, 2013. Carbon Dioxide Information Analysis Center, U.S. Department of Energy.

Cherubini, F., Peters, G.P., Berntsen, T., Strømman, A.H., Hertwich, E., 2011. CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy 3, 413–426.

Climate Interactive, 2013. Climate Interactive [WWW Document]. URL http://climateinteractive.org/

Collins, W.J., Derwent, R.G., Johnson, C.E., Stevenson, D.S., 2002. The Oxidation of Organic Compounds in the Troposphere and their Global Warming Potentials. Climatic Change 52, 453–479.

De Araujo, J.L., Rosa, L.P., da Silva, N.F., 2010. Hydroelectricity, in: Generating Electricity in a Carbon-Constrained World. Elsevier, pp. 323–344.

De Cara, S., Debove, E., Jayet, P.A., 2006. The Global Warming Potential Paradox: Implications for the Design of Climate Policy. UMR Economie Publique.

De Freitas, L.C., Kaneko, S., 2011. Decomposing the decoupling of CO2 emissions and economic growth in Brazil. Ecological Economics 70, 1459–1469.

De Lucena, A.F.P., Schaeffer, R., Szklo, A.S., 2010. Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. Global Environmental Change 20, 342–350.

Derwent, R.G., Stevenson, D.S., Doherty, R.M., Collins, W.J., Sanderson, M.G., Johnson, C.E., 2008. Radiative forcing from surface NO x emissions: spatial and seasonal variations. Climatic Change 88, 385–401.

Deuber, O., Luderer, G., Edenhofer, O., 2013. Physico-economic evaluation of climate metrics: A conceptual framework. Environmental Science & Policy 29, 37–45.

Eckhaus, R.S., 1992. Comparing the Effects of Greenhouse Gas Emissions on Global Warming. Energy Journal 13, 25–35.

EDGAR, 2013. Joint Research Centre - Emission Database for Global Atmospheric Research.

Edwards, P.N., 2010. A vast machine: computer models, climate data, and the politics of global warming. MIT Press, Cambridge, Mass.

Eletrobrás, 2013. Potencial Hidrelétrico Brasileiro (SIPOT).

EPE, 2007. National Energy Plan 2030 (Plano Nacional de Energia 2030), Energy Research Company (Empresa de Pesquisa Energética), Brasília 2007.

EPE, 2012. Electricity demand forecasts for the next 10 years (2013-2022), DEA Technical Note, Demand Studies Series - Projeção da demanda de energia elétrica para os próximos 10 anos (2013-2022). Nota técnica DEA 22/12. Série Estudos da demanda. Empresas de Pesquisa Energética, EPE, Rio de Janeiro, RJ, Brasil.

EPE, E. de P.E., 2011. Balanço Energético Nacional.

Fisher, D.A., Hales, C.H., Filkin, D.L., Ko, M.K.W., Sze, N.D., Connell, P.S., Wuebbles, D.J., Isaksen, I.S.A., Stordal, F., 1990. Model calculations of the relative effects of CFCs and their replacements on stratospheric ozone. Nature 344, 508–512.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., J. Lean, Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Dorland, R.V., 2007. Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Fuglestvedt, J.S., Berntsen T.K, O, G., R, S., K.P, S., T, S., 2003. Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices [WWW Document]. URL http://www.ingentaconnect.com/content/klu/clim/2003/00000058/00000003/05117436

Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Skodvin, T., 2000. Climate implications of GWP-based reductions in greenhouse gas emissions. Geophysical Research Letters 27, 409–412.

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M., Waitz, I.A., 2010. Transport impacts on atmosphere and climate: Metrics. Atmospheric Environment 44, 4648–4677.

Gian-Kasper, P., Stocker, T., Midgley, P., Tignor, M., 2009. IPCC Expert Meeting on the Science of Alternative Metrics (Meeting Report). IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.
Godal, O., 2003. The IPCC's Assessment of Multidisciplinary Issues: The Case of Greenhouse Gas Indices. Climatic Change 58, 24–249.
Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., Chateau, J., 2010. A global ranking of port cities with high exposure to climate extremes. Climatic Change 104, 89–111.
Hartmann, D.L., 1994. Global physical climatology, International geophysics. Academic Press, San Diego.
Houghton, R.A., 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus B 55, 378–390.
Houghton, R.A., 2008. Carbon Flux to the Atmosphere from Land-Use Changes: 1850-2005. TRENDS: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.
IBGE, 2013a. Instituto Brasileiro de Geografia e Estatística, Sala de Imprensa, Notícias, PPM 2011: Rebanho cresce 1,6% e chega a 212,8 milhões de cabeças.
IBGE, 2013b. Instituto Brasileiro de Geografia e Estatística [WWW Document]. URL http://www.ibge.gov.br/home/
IEA, 2011. World Energy Outlook 2011. IEA, International Energy Agency : OECD, Paris.
IEA, 2012a. World Energy Outlook 2012. IEA, International Energy Agency.
IEA, 2012b. Energy statistics of non-oecd countries. Oecd, Paris.
IPCC, 1995. Second Assessment Report: Climate Change 1995 (SAR), Working Group 1: The Science of Climate Change. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
IPCC, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change, FCCC/CP/1997/7/Add. 1.
IPCC, 2000. Emissions scenarios. a special report of IPCC Working Group III. Intergovernmental Panel on Climate Change, [Geneva].
IPCC, 2001. Third Assessment Report: Climate Change 2001 (TAR), Working Group 1:The Scientific Basis. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
IPCC, 2007. Fourth Assessment Report: Climate Change 2007 (AR4), Working Group 1 Report: The Physical Science Basis. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
IPCC, 2009. Summary Report of the IPCC Expert Meeting on the Science of Alternative Metrics 18–20 March 2009, Oslo, Norway.
Johansson, D.J.A., Persson, U.M., Azar, C., 2006. The cost of using global warming potentials: Analysing the trade off between CO2, CH4 and N2O. Climatic Change 77, 291–309.
Joos, F., Prentice, I.C., Sitch, S., Meyer, R., Hooss, G., Plattner, G.-K., Gerber, S., Hasselmann, K., 2001. Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) Emission Scenarios. Global Biogeochemical Cycles 15, 891–907.

Kandlikar, M., 1995. The relative role of trace gas emissions in greenhouse abatement policies. Energy Policy 23, 879–883.
Kandlikar, M., 1996. Indices for comparing greenhouse gas emissions: integrating science and economics. Energy Economics 18, 265–281.
Kendall, A., Chang, B., Sharpe, B., 2009. Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. Environmental science & technology 43, 7142–7147.
Lage, E.S., Processi, L.D., Souza, L.D.W., Dores, P.B., Galoppi, P.P.S., nd. Gás não convencional: experiência americana e perspectivas para o mercado brasileiro (Setorial, Petróleo e Gás No. 37). BNDES.
Lashof, D.A., Ahuja, D.R., 1990. Relative contributions of greenhouse gas emissions to global warming. Nature 344, 529–531.
Levasseur, A., Lesage, P., Margni, M., Deschênes, L., Samson, R., 2010. Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. Environmental Science & Technology 44, 3169–3174.
Levin, I., Naegler, T., Heinz, R., Osusko, D., Cuevas, E., Engel, A., Ilmberger, J., Langenfelds, R.L., Neininger, B., Rohden, C. v., Steele, L.P., Weller, R., Worthy, D.E., Zimov, S.A., 2010. The global SF_6 source inferred from long-term high precision atmospheric measurements and its comparison with emission inventories. Atmospheric Chemistry and Physics 10, 2655–2662.
Manne, A.S., Richels, R.G., 2001. An alternative approach to establishing trade-offs among greenhouse gases. Nature 410, 675–677.
Marais, K., Lukachko, S.P., Jun, M., Mahashabde, A., Waitz, I.A., 2008. Assessing the impact of aviation on climate. Meteorologische Zeitschrift 17, 157–172.
Margulis, S., Dubeux, C.S., 2011. The Economics of Climate Change in Brazil: Costs and Opportunities, FEA/USP, São Paulo.
MCT, 2004. Brazil's Initial National Communication to the United Nations Framework Convention on Climate Change.
MCT, 2010. Brazil's Second National Communication to the United Nations Framework Convention on Climate Change.
MCTI, 2007. Plano de Ação 2007/2010. Ministério de Ciência, Tecnologia e Inovação (MCTI).
Meira Filho, L.G., Miguez, J.D.G., 2000. Note on the time-dependent relationship between emissions of greenhouse gases and climate change. Ministry of Science and Technology, Brqazil.
Michaelis, P., 1992. Global warming: Efficient policies in the case of multiple pollutants. Environmental and Resource Economics 2, 61–77.
Miles, L., Grainger, A., Phillips, O., 2004. The impact of global climate change on tropical forest biodiversity in Amazonia. Global Ecology and Biogeography 13, 553–565.
MMA, 2008. Plano Nacional Sobre Mudança do Clima, Brasil (PNMC) - National Climate Change Plan, Brazil.
MMA, 2010. Política Nacional sobre Mudança do Clima, Decreto nº 7.390/2010.
Moura, M.C.P., Castelo Branco, D.A., Peters, G.P., Szklo, A., Schaeffer, R., 2012. How the choice of multi-gas equivalency metrics affects mitigation options: The case of CO2 capture in a Brazilian coal-fired power plant. Energy Policy Available online at http://authors.elsevier.com/sd/article/S0301421513004527.
NOAA, 2103. National Weather Service, Layers of the Atmosphere.

Nobre, C., Assad, E.D., Oyama, M.D., 2005. Mudança ambiental no Brasil: o impacto do aquecimento global nos ecossistemas da Amazônia e na agricultura. Scientific American Brasil Special Issue: A Terra na Estufa, 70–75.

Nobre, C., Sampaio, G., Salazar, L., 2007. Mudanças Climáticas e Amazônia. Ciência e Cultura, SBPC 59.

O'Hare, M., Plevin, R.J., Martin, J.I., Jones, A.D., Kendall, A., Hopson, E., 2009a. Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. Environmental Research Letters 4, 024001.

O'Hare, M., Plevin, R.J., Martin, J.I., Jones, A.D., Kendall, A., Hopson, E., 2009b. Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. Environmental Research Letters 4, 024001.

O'Neill, B.C., 2000. The Jury is Still Out on Global Warming Potentials. Climatic Change 44, 427–443.

O'Neill, B.C., 2003. Economics, Natural Science, and the Costs of Global Warming Potentials. Climatic Change 58, 251–260.

OECD/IEA, 2011. Are we entering a golden age of gas? World Energy Outlook 2011 Special Report, International Energy Agency, Paris.

Pacala, S., 2004. Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. Science 305, 968–972.

Peters, G.P., Aamaas, B., T. Lund, M., Solli, C., Fuglestvedt, J.S., 2011. Alternative "Global Warming" Metrics in Life Cycle Assessment: A Case Study with Existing Transportation Data. Environmental Science & Technology 45, 8633–8641.

Pétron, G., Frost, G., Miller, B.R., Hirsch, A.I., Montzka, S.A., Karion, A., Trainer, M., Sweeney, C., Andrews, A.E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokencky, E.J., Patrick, L., Moore, C.T., Ryerson, T.B., Siso, C., Kolodzey, W., Lang, P.M., Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., Tans, P., 2012. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. Journal of Geophysical Research 117.

Pielke, R.A., 2007. The honest broker: making sense of science in policy and politics. Cambridge University Press, Cambridge ; New York.

PNE, 2007. National Energy Plan 2030.

Prather, M.J., Holmes, C.D., Hsu, J., 2012. Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry. Geophysical Research Letters 39.

Reilly, J.M., Richards, K.R., 1993. Climate change damage and the trace gas index issue. Environmental & Resource Economics 3, 41–61.

Reisinger, A., Meinshausen, M., Manning, M., 2011. Future changes in global warming potentials under representative concentration pathways. Environmental Research Letters 6, 024020.

Rosa, L.P., dos Santos, M.A., Matvienko, B., dos Santos, E.O., Sikar, E., 2004. Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Regions. Climatic Change 66, 9–21.

Rosa, L.P., Santos, M.A.D., Matvienko, B., Sikar, E., Santos, E.O.D., 2006. Scientific Errors in the Fearnside Comments on Greenhouse Gas Emissions (GHG) from Hydroelectric Dams and Response to His Political Claiming. Climatic Change 75, 91–102.

Rosa, L.P., Schaeffer, R., 1995. Global warming potentials: The case of emissions from dams. Energy Policy 23, 149–158.

Rosman, P.C.C.C., Klein, A., Neves, C., Muehe, D., Carvalho, J., Araújo, M., 2009. Vulnerabilidades da Zona Costeira Brasileira às Mudanças Climáticas. PENO/COPPE/UFRJ.

Rotmans, J., Den Elzen, M.G.J., 1992. A model-based approach to the calculation of global warming potentials (GWP). International Journal of Climatology 12, 865–874.

Rypdal, K., Winiwarter, W., 2001. Uncertainties in greenhouse gas emission inventories — evaluation, comparability and implications. Environmental Science & Policy 4, 107–116.

Schmalensee, R., 1993. Comparing Greenhouse Gases for Policy Purposes. Energy Journal 14, 245–255.

Schneider, S.H., Dickinson, R.E., 1974. Climate modeling. Reviews of Geophysics 12, 447.

Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S., Sausen, R., 2005. Scientific Issues in the Design of Metrics for Inclusion of Oxides of Nitrogen in Global Climate Agreements. Proceedings of the National Academy of Sciences of the United States of America 102, 15768–15773.

Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S., Skeie, R.B., Stuber, N., 2007. Comparing the climate effect of emissions of short- and long-lived climate agents. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365, 1903–1914.

Shine, K.P., Fuglestvedt, J.S., Hailemariam, K., Stuber, N., 2005. Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. Climatic Change 68, 281–302.

Silveira, H.P., n.d. Adaptação do Setor Agrícola Brasileiro, em Mudanças Climáticas e Eventos Extremos no Brasil.

Skodvin, T., Fuglestvedt, J.S., 1997. A comprehensive approach to climate change: Political and scientific considerations. Ambio 26, 351–358.

Smith, S.J., Wigley, M.L., 2000a. Global Warming Potentials: 1. Climatic Implications of Emissions Reductions [WWW Document]. URL http://www.ingentaconnect.com/content/klu/clim/2000/00000044/00000004/00239819

Smith, S.J., Wigley, M.L., 2000b. Global Warming Potentials: 2.Accuracy. Climatic Change 44, 459–469.

Stern, N., 2006. Review on the Economics of Climate Change.

Stevenson, D.S., 2004. Radiative forcing from aircraft NO_x emissions: Mechanisms and seasonal dependence. Journal of Geophysical Research 109.

Svensson, F., Hasselrot, A., Moldanova, J., 2004. Reduced environmental impact by lowered cruise altitude for liquid hydrogen-fuelled aircraft. Aerospace Science and Technology 8, 307–320.

Tanaka, K., Johansson, D.J.A., O'Neill, B.C., Fuglestvedt, J.S., 2013. Emission metrics under the 2 °C climate stabilization target. Climatic Change 117, 933–941.

Tanaka, K., Peters, G.P., Fuglestvedt, J.S., 2010. Policy Update: Multicomponent climate policy: why do emission metrics matter? Carbon Management 1, 191–197.

UNEP, 2012. Mitigation Options of Greenhouse Gas (GHG) Emissions in Key Sectors in Brazil, UNEP, Global Environmet Facility (GEF).

UNFCCC, 1997. Implementation of the Berlin Mandate, Seventh Session of the Ad Hoc Group on the Berlin Mandate, July 31-August 7, 1997, UNFCCC.

UNFCCC, 2006. CLIMATE CHANGE: IMPACTS, VULNERABILITIES AND ADAPTATION IN DEVELOPING COUNTRIES. United Nations Framework Convention on Climate Change UNFCCC.

UNFCCC, 2010. Communication from the Brazilian Embassy to the UNFCCC. Berlin.

UNFCCC, 2012. Greenhouse gases, sectors and source categories, common metrics to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks, and other methodological issues. United Nations Framework Convention on Climate Change. FCCC/KP/CMP/2011/10/Add.1, decision 4/CMP.7.

UNFCCC, 2013. Text of the Convention. UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE.

Unger, N., Bond, T.C., Wang, J.S., Koch, D.M., Menon, S., Shindell, D.T., Bauer, S., 2010. Attribution of climate forcing to economic sectors. Proceedings of the National Academy of Sciences 107, 3382–3387.

Van Vuuren, D.P., Weyant, J., de la Chesnaye, F., 2006. Multi-gas scenarios to stabilize radiative forcing. Energy Economics 28, 102–120.

Wallington, T.J., Anderson, J.E., Mueller, S.A., Winkler, S., Ginder, J.M., Nielsen, O.J., 2011. Time Horizons for Transport Climate Impact Assessments. Environmental Science & Technology 45, 3169–3170.

WEO, 2012. World Energy Outlook 2012.

Wigley, T.M.L., 2005. Effect of climate sensitivity on the response to volcanic forcing. Journal of Geophysical Research 110.

Wild, O., Prather, M.J., Akimoto, H., 2001. Indirect long-term global radiative cooling from NO_x Emissions. Geophysical Research Letters 28, 1719–1722.

Wit, R.C.N., Boon, B.H., van Velzen, A., Cames, M., Deuber, O., Lee, D.S., 2005. Giving wings to emission trading Inclusion of aviati on under the European emission trading system (ETS): design and impacts (No. Report for the European Commission, DG Environment No. ENV.C.2/ETU/2004/0074r). Delft, Netherlands.

WMO, 2013. World Meteorological Organization.

World Bank, 2013. Economics of Adaptation to Climate Change: Country Case Studies.

Wuebbles, D., Jain, A., Patten, K.O., Grant, K.E., 1995. Sensitivity of direct global warming potentials to key uncertainties. Climatic Change 29, 265–297.

Zhang, H., Wu, J., Lu, P., 2011. A study of the radiative forcing and global warming potentials of hydrofluorocarbons. Journal of Quantitative Spectroscopy and Radiative Transfer 112, 220–229.

APPENDIX A – Total 2005 Brazilian emissions for 10 GHGs according to GWP-100 and GTP-100

Source: Prepared by author, based on (MCT, 2010).

Table A1 – Total 2005 Brazilian emissions for 10 GHGs

2005	Gg	GWP-100 (MCT)	CO_2-eq		GTP-100 (MCT)	CO_2-eq		% difference between totals
CO_2	1637907	1.00	1,637,906.50	74.70%	1.00	1,637,906.50	87.17 %	
CH4	18105.95	21.00	380,224.89	17.34%	5.00	90,529.74	4.82%	
N_2O	546.079	310.00	169,284.49	7.72%	270.00	147,441.33	7.85%	
HFC-125	0.125	2,800.00	350.00	0.02%	1,113.00	139.13	0.01%	
HFC-134a	2.282	1,300.00	2,966.60	0.14%	55.00	125.51	0.01%	
HFC-143a	0.093	3,800.00	353.40	0.02%	4,288.00	398.78	0.02%	
HFC-152a	0.175	140.00	24.50	0.00%	0.10	0.02	0.00%	
CF_4	0.124	6,500.00	806.00	0.04%	10,052.00	1,246.45	0.07%	
C_2F_6	0.01	9,200.00	92.00	0.00%	22,468.00	224.68	0.01%	
SF_6	0.025	23,900.00	597.50	0.03%	40,935.00	1,023.38	0.05%	
Total			2,192,605.88	1.00		1,879,035.50	1.00	85.70%

Notes: GWP and GTP values are as listed in the MCT Second Inventory. There are differences between these values and those derived from the models used in this study.

APPENDIX B - Implications for Brazilian COP-15 pledge

According to the announcement made at the 15th Conference of the Parties (COP 15), held at Copenhagen, the Brazilian government pledged to reduce the baseline emissions in 2020 between 36.1% and 38.9%. According to the UNFCCC, the Brazilian government forecast this emission to be approximately 2700 Mt CO_2-equivalent[59], and so the mitigation range would therefore be between 974 and 1051 Mt CO_2-equivalent, distributed among various sectors. The table below shows this distribution:

Table B1- Brazilian COP-15 emission mitigation pledge per sector.

Sector	Mitigation effort	Mt CO_2-eq	
Land-use and change	Reduction in Amazon deforestation	564	24.8%
	Reduction in cerrado deforestation	104	
Agriculture and livestock	Reduction in grazing land deforestation	83-104	4.9% to 6.1%
	Integrated crop-livestock system	18-22	
	No-till farming	16-20	
	Biological N2 fixation	16-20	
Energy	Energy efficiency	12-15	6.1% to 7.7%
	Increase in use of biofuels	48-60	
	Increase in supply of hydroelectric	79-99	
	Alternative energy sources	26-33	
Other	Iron and steel	8-10	0.3% to 0.4%
Total mitigation		974- 1051	36.1% to 38.9%
Baseline in 2020		2698	100%

Source: UNFCCC, 2010.

Although it wasn't possible to obtain access to the methodology used to determine these sectoral contributions, we assume that the GWP-100 metric was used, and we also assume a mix of the 3 main GHGs, for the sake of simplicity. Even if the actual methodology used by the Brazilian government is founded on different assumptions, we are interested here in using this case as an example of the challenges facing policymakers, and our analysis is instructive as long as the assumptions made are clear.

To determine the degree of flexibility allowed by the pledge for each sector, a reverse analysis was conducted as follows. We assumed that each sector's GHG emissions are distributed in the same relative proportions as in the MCT II data, available from the

[59] The Ministry of the Environment lists a different baseline total of 3235 Mt CO2-equivalent (MMA, 2010) . Here we have chosen to work with the estimate given by the UNFCCC (UNFCCC, 2010)

data assembled in Section 5.2. These percentages are also shown in Table B2. In conjunction with the mitigation percentages for each sector, shown in Table B1, we calculated the CO_2-equivalent emissions permitted for each GHG for each sector, according to 4 different metrics: fixed GWP and fixed GTP for the two time-horizons 50 and 100. It should be noted that in the analysis in Chapters 6 and 7, the variability of the total multi-gas CO_2-equivalent was calculated, but that here, it is assumed that the total multi-gas CO_2-equivalents are the same for all metrics, since we are working backwards from that assumption. The percentages in Table B4 are for individual the GHGs are therefore not comparable to the ones in the diagrams of Section 6.3, which are for the multi-gas totals.

We limited this analysis to these fixed metrics for several reasons: first, as was seen in Section 7.5, the comparison between GWP and GTP is the most relevant and produced the largest variability; second, the results for a comparison between the variable GWP and GTP are similar to the results for the comparison between fixed GWP and GTP, so we can use these results as a a general guideline for the variable comparison, if necessary; third, as was seen in the analysis performed in Chapters 6 and 7 shows that for CH_4 and N_2O looked at individually the largest variability was for the 2050 and 2100, so these are the worst-cases and the analysis is therefore conservative; fourth, a backwards analysis for variable metrics can be quite complex.

We calculated the CO_2-equivalent emissions for the GHGs based on the 4 metrics, shown in Table B2. Absolute emissions are shown in Table B3 and the percentage differences for the CO_2-equivalent metric comparisons are shown in Table B4.

Table B2– Estimates of GHG emissions based on Brazilian COP-15 pledge – CO_2-equivalents

	Mt CO_2-eq	CO_2 (99.76%)	CH_4 (0.24%)	N_2O (0%)	Total
Land-use	GWP-100	630.53	38.59	0	669.12
	GTP-100	662.97	6.15	0	669.12
	GWP-50	606.62	62.50	0	669.12
	GTP-50	649.15	19.97	0	669.12
	Mt CO_2-eq	**CO_2 (0%)**	**CH_4 (96.52%)**	**N_2O (3.48%)**	**Total**
Agriculture and livestock	GWP-100	0	92.85	39.36	132.20
	GTP-100	0	37.90	94.30	132.20
	GWP-50	0	104.97	27.24	132.20
	GTP-50	0	69.20	63.00	132.20
	Mt CO_2-eq	**CO_2 (99.87%)**	**CH_4 (0.12%)**	**N_2O (0.01%)**	**Total**
Energy	GWP-100	155.19	4.74	4.65	164.58
	GTP-100	159.59	0.74	4.25	164.58
	GWP-50	152.06	7.83	4.69	164.58
	GTP-50	157.09	2.41	5.08	164.58

Source: Prepared by the author

Table B3- Estimates of GHG emissions based on Brazilian COP-15 pledge – absolute emissions

	Mt CO_2-eq	CO_2 (99.76%)	CH_4 (0.24%)	N_2O (0%)	Total
Land-use	GWP-100	630.53	1.52	0.00	632.05
	GTP-100	662.97	1.59	0.00	664.56
	GWP-50	606.62	1.46	0.00	608.08
	GTP-50	649.15	1.56	0.00	650.71
	Mt CO_2-eq	**CO_2 (0%)**	**CH_4 (96.52%)**	**N_2O (3.48%)**	**Total**
Agriculture and livestock	GWP-100	0.00	3.65	0.13	3.78
	GTP-100	0.00	9.83	0.35	10.18
	GWP-50	0.00	2.45	0.09	2.54
	GTP-50	0.00	5.41	0.20	5.61
	Mt CO_2-eq	**CO_2 (99.87%)**	**CH_4 (0.12%)**	**N_2O (0.01%)**	**Total**
Energy	GWP-100	155.19	0.19	0.02	155.39
	GTP-100	159.59	0.19	0.02	159.80
	GWP-50	152.06	0.18	0.02	152.26
	GTP-50	157.09	0.19	0.02	157.29

Source: Prepared by the author

Table B4– Comparison between fixed GWP and GTP for Brazilian pledge

Mt CO_2-eq		CH_4 Fixed GWP vs. fixed GTP	N_2O Fixed GWP vs. fixed GTP
Land-use	50	213.0%	
	100	527.3%	
Agriculture and livestock	50	51.7%	.56.8%
	100	145.0%	-58.3%
Energy	50	224.2%	-7.6%
	100	541.4%	9.3%

Notes: Percentages are (GWP-GTP)/GTP.
Source: Prepared by the author

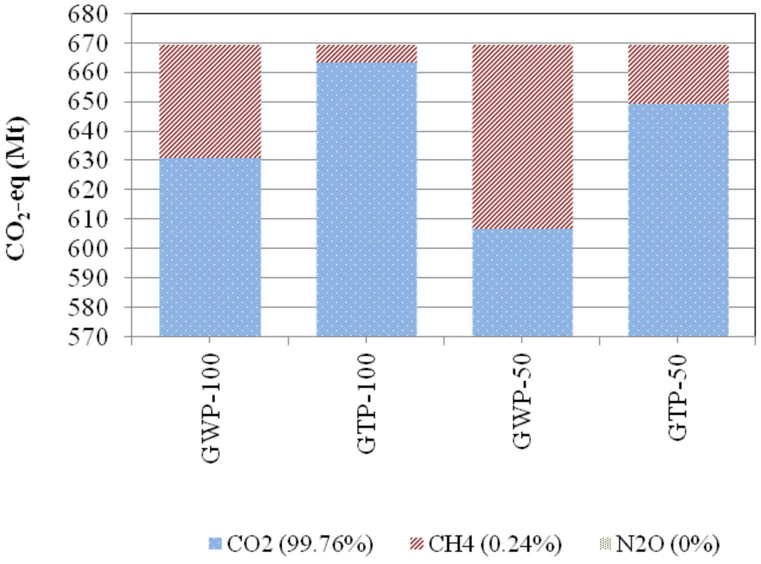


Figure B1 - Brazilian pledge: Land-use mitigation options.

24.8 % of 974 Mt CO2-eq total

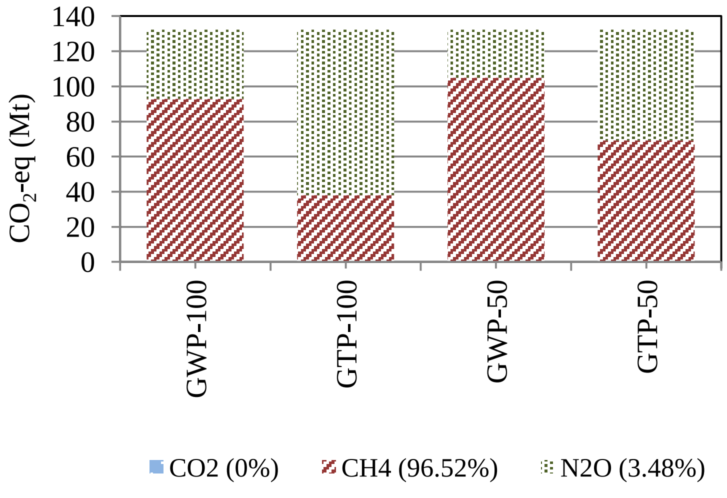


Figure B2- Brazilian pledge: Agriculture and livestock mitigation options. 4.9 % of 974 Mt CO2-eq total

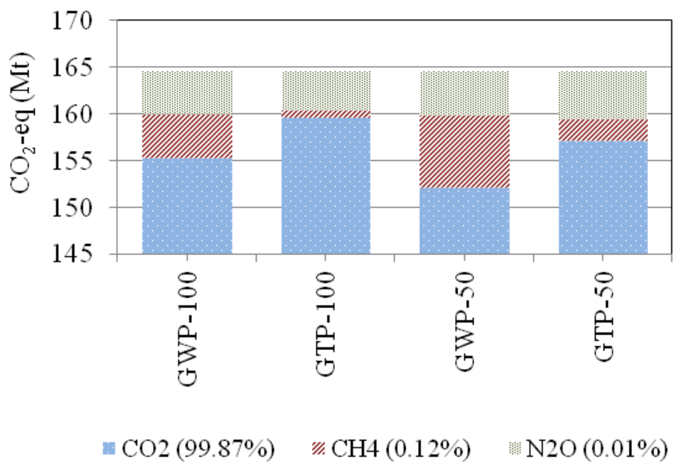


Figure B3- Brazilian pledge: Energy mitigation options. 4.9 % of 974 Mt CO2-eq total

It should be noted that the ratios between GWP and GTP are not exactly those of Table 26, since in this reverse analysis the total CO_2-equivalent is fixed, and so the total absolute emissions for the GWP and GTP cases are not the same, as they were before. The ratios in Table 26 must hence be multiplied by the ratio of the absolute emissions to obtain the ratios for the reverse analysis. For instance, for CH_4 for a time-horizon of 100, the ratio for land-use is 38.59/6.15 = 6.27. We are allowed 632.05 Mt of absolute emissions according to GWP-100 and 664.56 Mt according to GWP-100. This ratio, 632.05/664.56= 0.95, is the factor which the 6.6 ratio in Table 26 must be multiplied by to obtain the ratio here: $0.95 \cdot 6.6 = 6.27$.

For all 3 sectors, the largest allowance for CH_4 is for GWP-based impact, for impact 50 years into the future (for land-use, 62.5 Mt CO_2-eq), in 2070, followed by impact in 2120 (for land-use 38.59 Mt CO_2-eq). The smallest allowances are for GTP-based impact, where for impact in 2070 the allowance is larger (for land-use 19.97 Mt CO_2-eq) than for impact in 2120 (for land-use 6.15 Mt CO_2-eq). These trends are expected for all sectors, for the difference between GWP and GTP is more significant for time-horizons further away. Instead of regarding these shares as being 'allowances', policymakers can also see these as burden-sharing comparisons. In other words, for a GWP based land-use impact in 2070, CH_4 bears a larger part of the mitigation burden (3 times larger) than from a GTP-50 perspective.

For the energy sector, the differences are larger, as can be seen in Table B4, but it is important to see that the emission values for CH_4 are much smaller. For GWP-100, we have an allowance of 4.74 Mt CO_2-eq and for GTP-100, of 0.74 Mt CO_2-eq, so even though the difference is large, the emission volumes are not significant. The absolute emissions for all metrics are very similar for this sector.

For the agriculture and livestock sector, the differences aren't large, but the emission values for CH_4 are significant. If impact according to GWP-100 is considered, a mitigation of 132 Mt CO_2-eq can be reached by considering CH_4 to be 6 times more harmful if the GWP-100 metric is used than if the GTP-100 metric is used. The absolute emissions for CH_4 vary from 2.45 Mt – 3.65 Mt – 5.41 Mt – 9.83 Mt for GWP-50, GWP-100, GTP-50 and GTP-100, respectively. In other words, the mitigation target can be reached with very different absolute emission values, where GTP-100 allows for 4 times as much emission as GWP-50.

For the land-use sector, even though the major contribution is from CO_2, if impact according to GWP-100 is considered, a mitigation of 670 Mt CO_2-eq can be reached by considering CH_4 to be twice as harmful if the GWP-100 metric is used than if the GTP-100 metric is used.

APPENDIX C - IPCC Emission Factors

Source: IPCC, 2006

Table C1 – IPCC CO_2 Emission Factors

CO_2 Emission factors from IPCC (kg/TJ)	Energy Industries	Manufacturing industries and construction	Commercial/ Institutional	Residential/ agriculture/ forestry/fishing	Transportation
Crude oil and natural gas imported	73300	73300	73300	73300	73300
Natural gas	56100	56100	56100	56100	56100
Steam coal	91666.67	91666.67	91666.67	91666.67	91666.67
Metallurgical coal	94600	94600	94600	94600	94600
Uranium U3O8	0	0	0	0	0
Hydraulic energy	0	0	0	0	0
Firewood	0	0	0	0	0
Sugar-cane products (molasses, juice, bagasse)	0	0	0	0	0
Other primary sources (vegetable+industrial residues for steam+heat)	0	0	0	0	0
Total primary energy	0	0	0	0	0
Diesel oil	74100	74100	74100	74100	74100
Fuel oil imported	77400	77400	77400	77400	77400
Gasoline	69300	69300	69300	69300	69300
Liquefied Petroleum Gases	64200	64200	64200	64200	63100
Naptha	73300	73300	73300	73300	73300
Kerosene	71500	71500	71500	71500	71900
Gas coke	44400	44400	44400	44400	44400
Coal coke	107000	107000	107000	107000	107000
Uranium contained in UO2	0	0	0	0	0
Electricity	0	0	0	0	0
Charcoal	0	0	0	0	0
Anhydrous+hydrated ethyl alcohol	0	0	0	0	0
Other secondary oil products (refinery gas, coke etc)	97500	97500	97500	97500	73300
Non-energy oil products (grease,lubricant, paraffin wax,asphalt,solvent etc)	0	0	0	0	0
Bitumen or tar	80700	80700	80700	80700	0

Table C2 - IPCC CH_4 Emission Factors

CH_4 Emission factors from IPCC (kg/TJ)	Energy Industries	Manufacturing industries and construction	Commercial/ Institutional	Residential/ agriculture/ forestry/fishing	Transportation
Crude oil and natural gas	3	3	10	10	0
Natural gas	1	1	5	5	92
Steam coal	1	10	10	300	0
Metallurgical coal	1	10	10	300	0
Uranium U3O8	0	0	0	0	0
Hydraulic energy	0	0	0	0	0
Firewood	30	30	300	300	0
Sugar-cane products (molasses, juice, bagasse)	30	30	300	300	0
Other primary sources (vegetable+industrial residues for steam+heat)	30	30	300	300	0
Total primary energy	0	0	0	0	0
Diesel oil	3	3	10	10	3.9
Fuel oil imported	3	3	10	10	0
Gasoline	3	3	10	10	33
Liquefied Petroleum Gases	3	3	10	10	62
Naptha	3	3	10	10	0
Kerosene	3	3	10	10	0
Gas coke	1	1	5	5	0
Coal coke	1	10	10	300	0
Uranium contained in UO_2	0	0	0	0	0
Electricity	0	0	0	0	0
Charcoal	200	200	200	200	0
Anhydrous+hydrated ethyl alcohol	0	0	0	0	18
Other secondary oil products (refinery gas, coke etc)	3	3	10	10	0
Non-energy oil products (grease,lubricant, paraffin wax,asphalt,solvent etc)	0	0	0	0	0
Bitumen or tar	1	10	10	300	0

1

Table C3 - IPCC N_2O Emission Factors

N_2O Emission factors from IPCC (kg/TJ)	Energy Industries	Manufacturing industries and construction	Commercial/ Institutional	Residential/ agriculture/ forestry/fishing	Transportation
Crude oil and natural gas	0.6	0.6	0.6	0.6	0
Natural gas	0.1	0.1	0.1	0.1	3
Steam coal	1.5	1.5	1.5	1.5	0
Metallurgical coal	1.5	1.5	1.5	1.5	0
Uranium U3O8	0	0	0	0	0
Hydraulic energy	0	0	0	0	0
Firewood	4	4	4	4	0
Sugar-cane products (molasses, juice, bagasse)	4	4	4	4	0
Other primary sources (vegetable+industrial residues for steam+heat)	4	4	4	4	0
Total primary energy	0	0	0	0	0
Diesel oil	0.6	0.6	0.6	0.6	3.9
Fuel oil imported	0.6	0.6	0.6	0.6	0
Gasoline	0.6	0.6	0.6	0.6	3.2
Liquefied Petroleum Gases	0.6	0.6	0.6	0.6	0.2
Naptha	0.6	0.6	0.6	0.6	0
Kerosene	0.6	0.6	0.6	0.6	0
Gas coke	0.1	0.1	0.1	0.1	0
Coal coke	1.5	1.5	1.5	1.5	0
Uranium contained in UO_2	0	0	0	0	0
Electricity	0	0	0	0	0
Charcoal	4	4	1	1	0
Anhydrous+hydrated ethyl alcohol	0	0	0	0	0
Other secondary oil products (refinery gas, coke etc)	0.6	0.6	0.6	0.6	0
Non-energy oil products (grease,lubricant, paraffin wax,asphalt,solvent etc)	0	0	0	0	0
Bitumen or tar	1.5	1.5	1.5	1.5	0

APPENDIX D – Sectoral Energy Consumption for 1970-2010

Source: Prepared by author, based on BEB (BEN, 2011)

Energy unit : 10^3 toe

Table D1 – Sectoral Energy Consumption for 1970-2010

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
1-NUCLEAR FUEL CYCLE	0	0	0	0	0	0	0	0	0	0
2-POWER PLANTS public service	4556	5335	5492	6249	6658	7205	8036	9113	10463	11392
3-POWER PLANTS auto-generators	728	640	695	734	770	840	880	972	1077	1264
4-CHARCOAL PRODUCERS	3494	3979	4611	4894	6103	7297	6620	6730	6888	8110
5-ENERGY	1373	1718	1848	2305	2767	2928	3100	3628	4567	5577
6-RESIDENTIAL	21357	21461	21587	21413	21283	20913	20658	19940	19192	19178
7-COMMERCIAL	406	418	446	462	483	501	525	538	554	580
8-PUBLIC	111	141	170	195	182	207	212	177	202	211
9-AGRICULTURE AND LIVESTOCK	5324	5284	5300	5397	5320	5284	5352	5411	5258	5428
10-TRANSPORTATION: ROAD	11361	12426	14060	16476	17344	18525	19895	19898	21582	22491
11-TRANSPORTATION:RAIL	475	443	441	471	540	549	572	548	554	601
12-TRANSPORTATION:AIR	712	820	928	1095	1248	1327	1468	1497	1537	1760
13-TRANSPORTATION:WATERWAYS	588	678	803	993	1703	1725	1886	1470	1767	2055
14-INDUSTRY: CEMENT	1203	1294	1454	1610	1794	1905	2297	2468	2635	2566
15-INDUSTRY: PIG-IRON AND STEEL	3112	3322	3717	3902	4556	5424	5479	6332	6511	7600
16-INDUSTRY: IRON-ALLOYS	50	53	58	83	98	115	132	158	187	211
17-INDUSTRY: MINING AND PELLETIZATION	224	274	280	367	489	576	682	746	874	985
18-INDUSTRY: NON-FERROUS AND THE OTHER METALLURGICAL	168	212	245	282	319	352	413	471	643	717
19-INDUSTRY: CHEMICAL	938	1138	1226	1568	1520	1623	1829	1991	2265	2698
20-INDUSTRY: FOOD AND BEVERAGE	5559	5836	6300	6617	6652	6245	6931	7772	7368	7093
21-INDUSTRY: TEXTILES	617	654	658	693	715	736	793	797	770	798
22-INDUSTRY: PULP AND PAPER	791	894	1001	1156	1317	1286	1424	1613	1800	2001
23-INDUSTRY: CERAMICS	1494	1433	1566	1809	1939	1995	2125	2065	2166	2215
24-INDUSTRY: OTHER	1364	1587	1601	2141	2265	2387	2944	2940	3112	3129
25-UNIDENTIFIED CONSUMPTION	0	0	0	0	8	23	0	28	42	1
TOTAL FUEL COMBUSTION PER YEAR	66003	70042	74490	80911	86071	89970	94254	97304	102015	108661

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
1-NUCLEAR FUEL CYCLE	0	0	1176	0	0	0	0	829	360	0
2-POWER PLANTS public service	12344	12836	13405	14028	16278	17656	18859	18766	19446	20000
3-POWER PLANTS auto-generators	1382	1418	1470	1601	1661	1627	1880	1934	1981	1913
4-CHARCOAL PRODUCERS	9182	8721	8837	9938	12283	12865	13579	13212	14070	15653
5-ENERGY	5515	5554	6564	8203	9412	10980	10425	12164	11725	11973
6-RESIDENTIAL	18957	18568	17127	16311	16512	15741	14842	15551	15221	14750
7-COMMERCIAL	607	645	643	620	529	553	619	614	695	781
8-PUBLIC	265	190	201	207	193	193	157	245	367	159
9-AGRICULTURE AND LIVESTOCK	5577	5510	5535	5630	5407	5674	5519	5882	5926	5986
10-TRANSPORTATION: ROAD	21611	21014	21460	20549	21070	22124	26340	26306	26817	28905
11-TRANSPORTATION:RAIL	618	597	581	590	594	602	606	578	608	619
12-TRANSPORTATION:AIR	1735	1948	1982	1977	1755	1857	2011	2031	1967	2078
13-TRANSPORTATION:WATERWAYS	1681	2049	2275	2151	2215	2626	2067	1737	1631	1042
14-INDUSTRY: CEMENT	2480	2508	2528	1902	1665	1887	2141	2160	2086	1971
15-INDUSTRY: PIG-IRON AND STEEL	7927	6607	6675	7508	9643	10344	10960	11834	13010	13589
16-INDUSTRY: IRON-ALLOYS	253	289	271	335	376	449	474	478	578	696
17-INDUSTRY: MINING AND PELLETIZATION	1021	821	809	650	809	803	826	818	883	850
18-INDUSTRY: NON-FERROUS AND THE OTHER METALLURGICAL	764	633	625	789	807	931	870	1085	1132	1080
19-INDUSTRY: CHEMICAL	3055	2996	3082	2724	2852	2984	3066	3253	3204	3146
20-INDUSTRY: FOOD AND BEVERAGE	7593	7677	7877	8533	8303	7904	7945	8713	7919	7157
21-INDUSTRY: TEXTILES	754	648	706	626	504	551	646	708	675	702
22-INDUSTRY: PULP AND PAPER	2226	2115	2230	2283	2362	2598	2770	2802	2952	2953
23-INDUSTRY: CERAMICS	2345	2015	1838	2180	2358	2317	2630	2597	2501	2562
24-INDUSTRY: OTHER	3210	2082	2258	1753	1823	1935	2195	2332	2316	2123
25-UNIDENTIFIED CONSUMPTION	0	0	130	124	0	0	0	104	92	91
TOTAL FUEL COMBUSTION PER YEAR	111100	107440	110286	111210	119409	125201	131429	136733	138163	140777

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
1-NUCLEAR FUEL CYCLE	0	1176	0	440	1374	771	0	7320	5085	195
2-POWER PLANTS public service	19787	20776	21450	21930	22664	24925	26076	27988	29580	31532
3-POWER PLANTS auto-generators	2146	2296	2659	2770	2616	2787	3254	3463	3718	4363
4-CHARCOAL PRODUCERS	12780	11208	10290	10831	10965	10092	8946	8605	7836	8491
5-ENERGY	11454	11881	11684	11798	12657	12119	13067	14637	13541	12551
6-RESIDENTIAL	13864	13950	14109	13286	13069	12626	12721	12808	12973	13303
7-COMMERCIAL	888	831	849	679	677	675	700	741	769	811
8-PUBLIC	173	178	170	290	630	669	484	541	619	817
9-AGRICULTURE AND LIVESTOCK	5454	5519	5426	5745	5931	6262	6441	6600	6311	6447
10-TRANSPORTATION: ROAD	29276	30751	30878	32012	34025	37250	40295	42530	44124	43412
11-TRANSPORTATION:RAIL	530	527	540	549	411	441	406	329	350	350
12-TRANSPORTATION:AIR	1967	2059	1936	2044	2097	2436	2600	2926	3207	2989
13-TRANSPORTATION:WATERWAYS	1089	1044	1094	1239	1123	1105	1384	998	1070	1096
14-INDUSTRY: CEMENT	2014	2095	1711	1744	1749	2077	2487	2785	2921	2926
15-INDUSTRY: PIG-IRON AND STEEL	11126	11533	11442	12281	12800	12727	12479	12993	12698	12680
16-INDUSTRY: IRON-ALLOYS	411	530	479	589	514	431	651	464	507	538
17-INDUSTRY: MINING AND PELLETIZATION	778	770	833	862	980	1008	1167	1148	1184	1403
18-INDUSTRY: NON-FERROUS AND THE OTHER METALLURGICAL	1148	1112	1134	1267	1210	1441	1614	1450	1521	1685
19-INDUSTRY: CHEMICAL	3089	3124	3181	3050	3249	3502	3892	4572	4259	4745
20-INDUSTRY: FOOD AND BEVERAGE	7457	7505	8505	8510	9908	10182	10565	11124	12377	13162
21-INDUSTRY: TEXTILES	673	645	589	623	545	544	611	510	510	470
22-INDUSTRY: PULP AND PAPER	2951	3086	3586	3756	3956	4024	4243	4212	4670	4992
23-INDUSTRY: CERAMICS	2173	2111	2124	2318	2366	2348	2524	2661	2718	2729
24-INDUSTRY: OTHER	2046	2044	1849	2029	2183	2274	2261	2472	2512	2565
25-UNIDENTIFIED CONSUMPTION	311	0	141	0	0	0	0	393	44	0
TOTAL FUEL COMBUSTION PER YEAR	133584	136750	136659	140642	147698	152714	158868	174269	175105	174253

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1-NUCLEAR FUEL CYCLE	2028	4522	5954	4483	5904	4612	5473	6002	4573	3871	4821
2-POWER PLANTS public service	32863	32788	32677	33858	36294	37288	39142	40251	43347	40745	46425
3-POWER PLANTS auto-generators	4697	5301	5848	6038	6532	6867	7151	7738	8830	9084	10946
4-CHARCOAL PRODUCERS	9284	8626	9034	10626	12308	12173	11875	12137	12056	7805	8637
5-ENERGY	11946	12616	13391	14799	15307	16479	17570	19551	22964	22801	23482
6-RESIDENTIAL	13501	13807	14427	14353	14600	14672	14710	14456	14518	14474	14342
7-COMMERCIAL	884	941	1032	834	881	851	882	901	815	782	735
8-PUBLIC	732	754	775	661	685	636	610	657	595	561	456
9-AGRICULTURE AND LIVESTOCK	6217	6663	6701	6923	6995	7009	7138	7554	8322	8026	8392
10-TRANSPORTATION: ROAD	42766	42946	44459	44329	47334	48073	49067	52892	57370	57683	63963
11-TRANSPORTATION:RAIL	403	457	454	552	557	564	555	581	626	633	703
12-TRANSPORTATION:AIR	3182	3271	3134	2241	2392	2596	2435	2674	2857	2875	3241
13-TRANSPORTATION:WATERWAYS	926	1024	1036	954	1096	1124	1088	1338	1452	1359	1380
14-INDUSTRY: CEMENT	2980	3006	2790	2481	2326	2486	2733	3002	3331	3268	3711
15-INDUSTRY: PIG-IRON AND STEEL	14020	13567	14440	15320	16492	16062	15534	16662	16627	12357	15206
16-INDUSTRY: IRON-ALLOYS	632	470	549	856	905	948	950	1057	1060	867	968
17-INDUSTRY: MINING AND PELLETIZATION	1674	1674	1696	1710	1843	2076	2150	2414	2380	1701	2349
18-INDUSTRY: NON-FERROUS AND THE OTHER METALLURGICAL	1874	1746	1887	2251	2382	2431	2520	2709	2608	2496	2540
19-INDUSTRY: CHEMICAL	4938	4936	5072	4917	5256	5354	5484	5672	5307	4817	5291
20-INDUSTRY: FOOD AND BEVERAGE	11124	13051	14290	15046	15892	16149	18274	19336	18709	19638	21457
21-INDUSTRY: TEXTILES	524	492	527	480	517	543	544	590	536	494	498
22-INDUSTRY: PULP AND PAPER	5162	5148	5459	5961	6086	6413	6686	7129	7430	7940	8420
23-INDUSTRY: CERAMICS	2834	2760	2819	2881	2953	3142	3257	3556	3859	3806	4176
24-INDUSTRY: OTHER	2828	2687	2723	2643	2768	2810	2851	3164	3520	3283	3755
25-UNIDENTIFIED CONSUMPTION	0	0	0	0	0	0	0	0	0	0	0
TOTAL FUEL COMBUSTION PER YEAR	178019	183254	191172	195197	208304	211360	218680	232024	243694	231364	255895

APPENDIX E – Sectoral Energy Consumption Graphs for 1970-2010

Source: Prepared by author, based on BEB (BEN, 2011)

Energy unit (y-axis): 10^3 toe

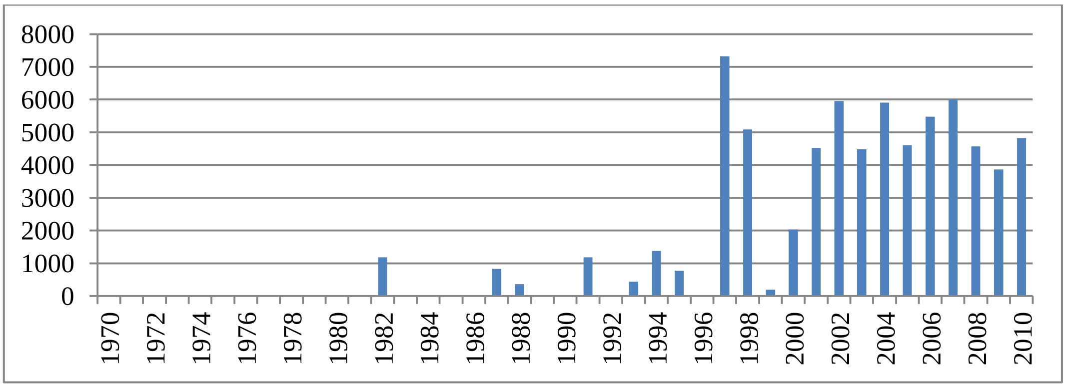


Figure E1 – Nuclear Fuel Cycle

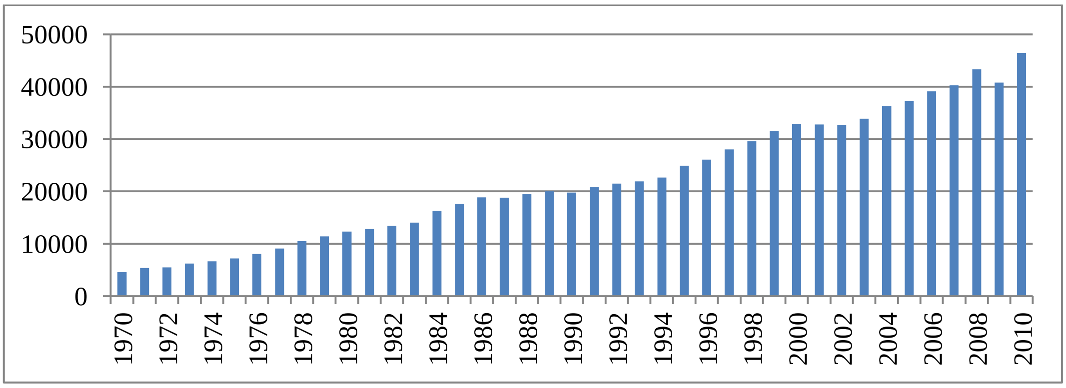


Figure E2 -Power Plants – Public Service

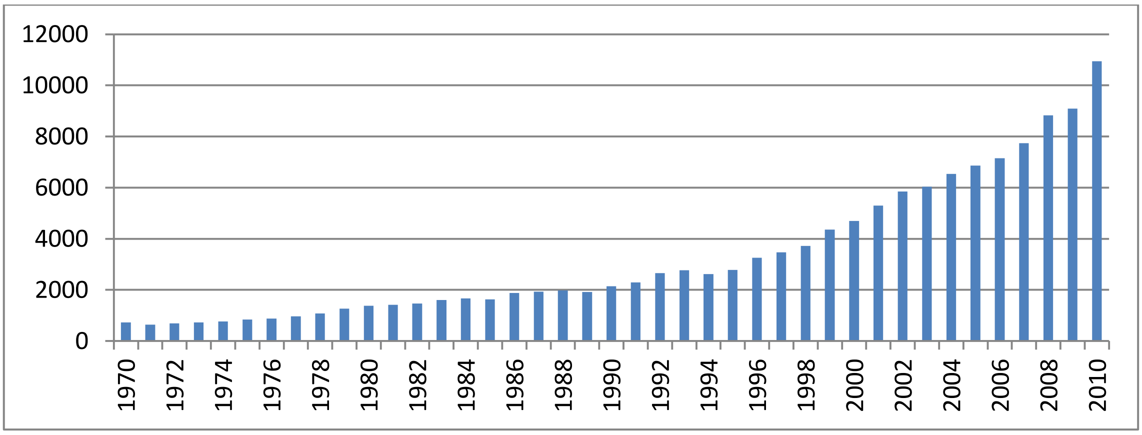


Figure E3 - Power Plants - Auto generators

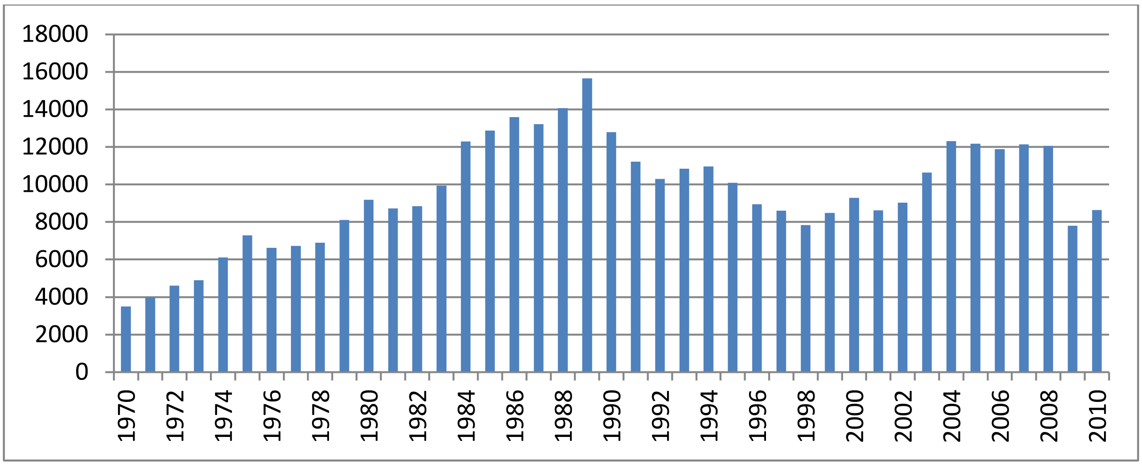


Figure E4 - Charcoal Producers

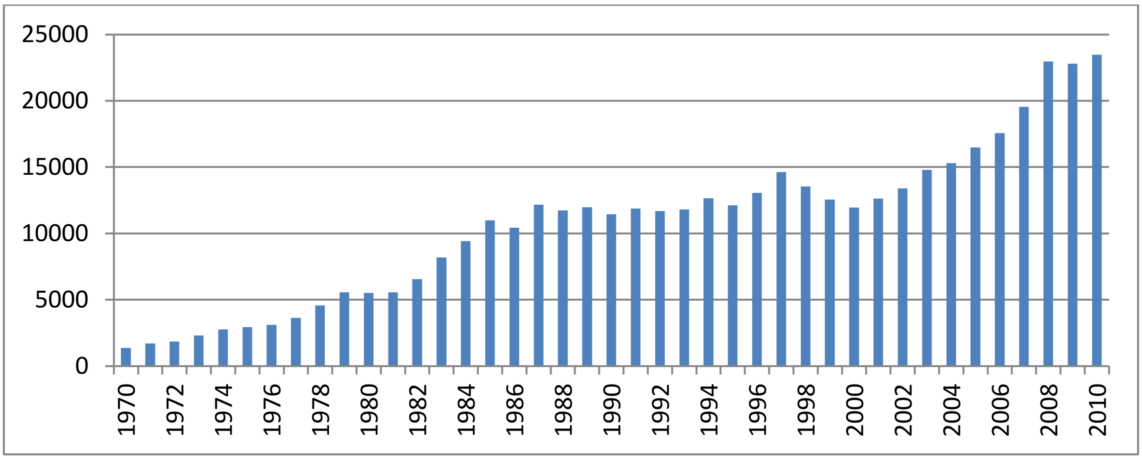


Figure E5 - Energy

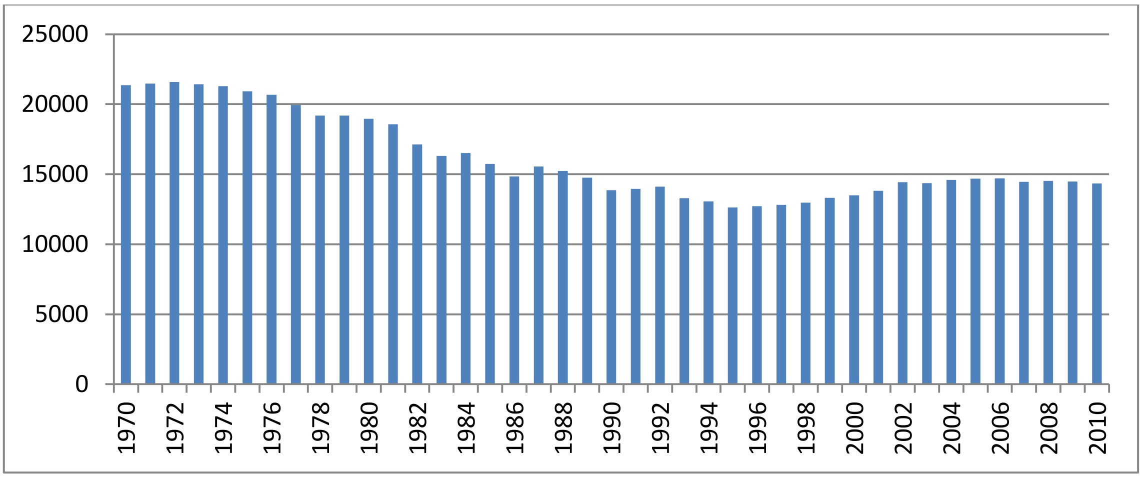


Figure E6 - Residential

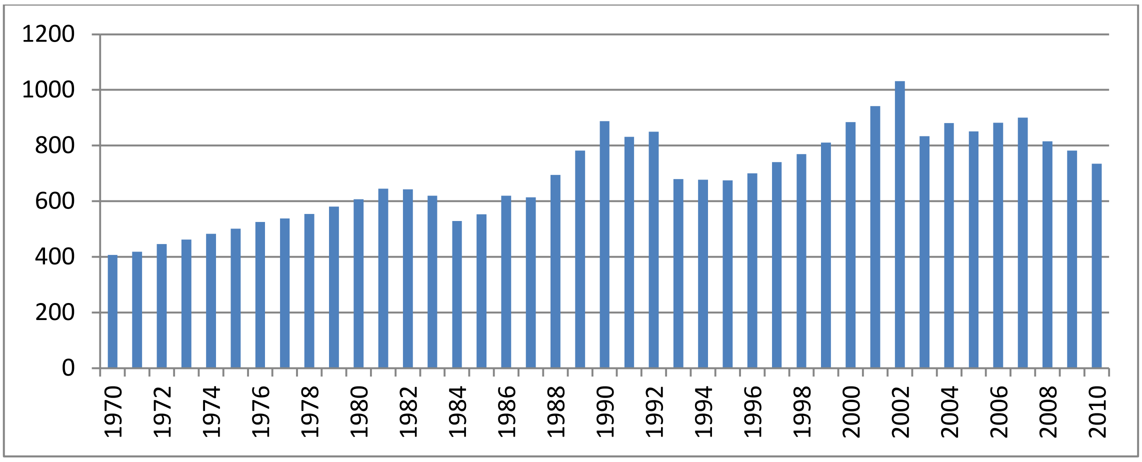


Figure E7 - Commercial

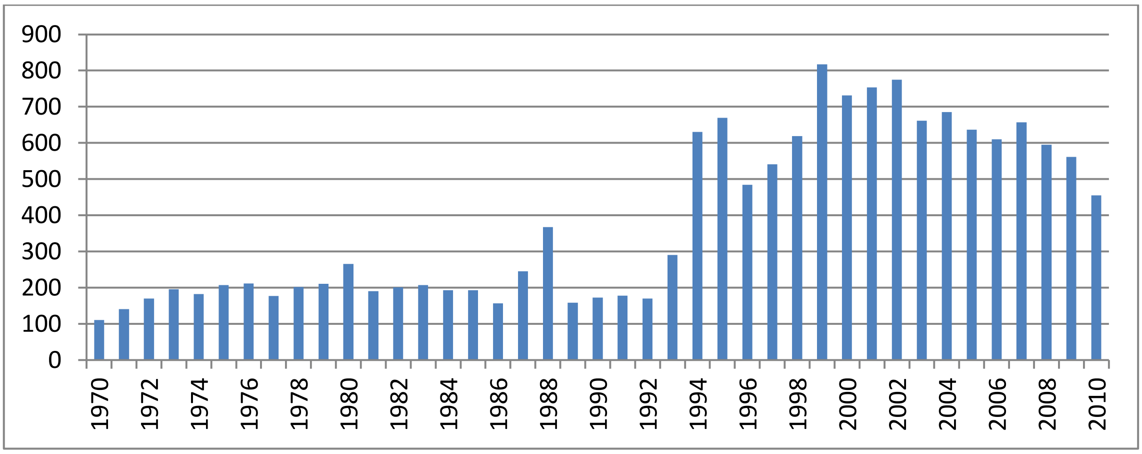


Figure E8 - Public

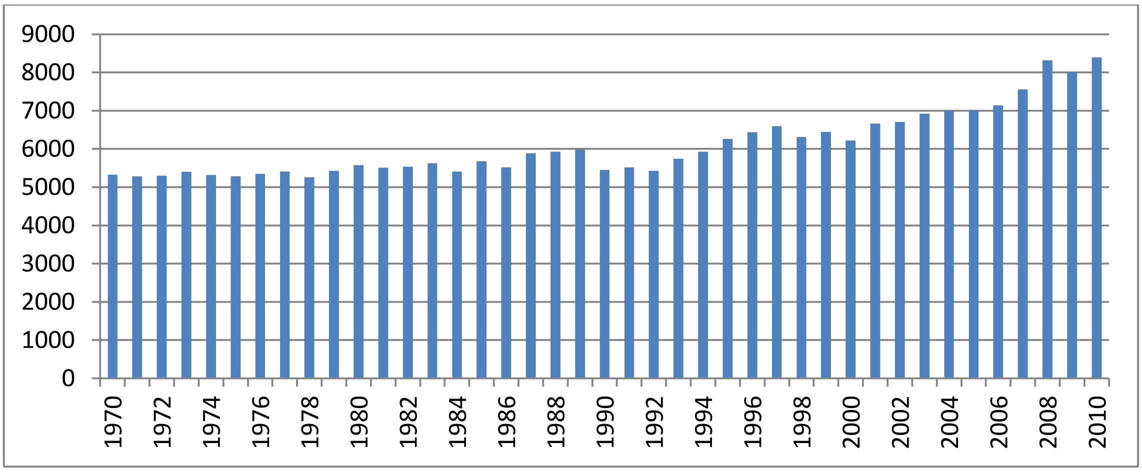


Figure E9 - Agricultural and livestock

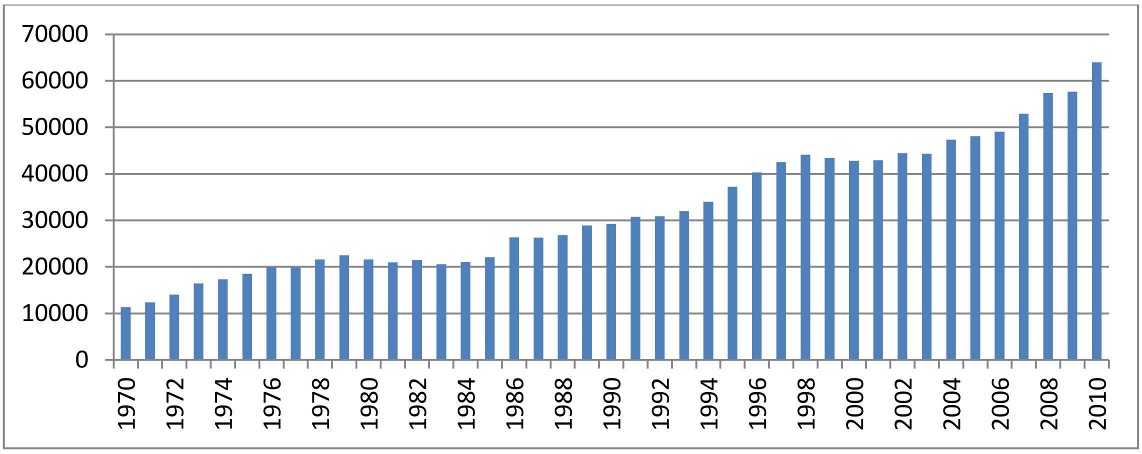


Figure E10 - Transportation: Road

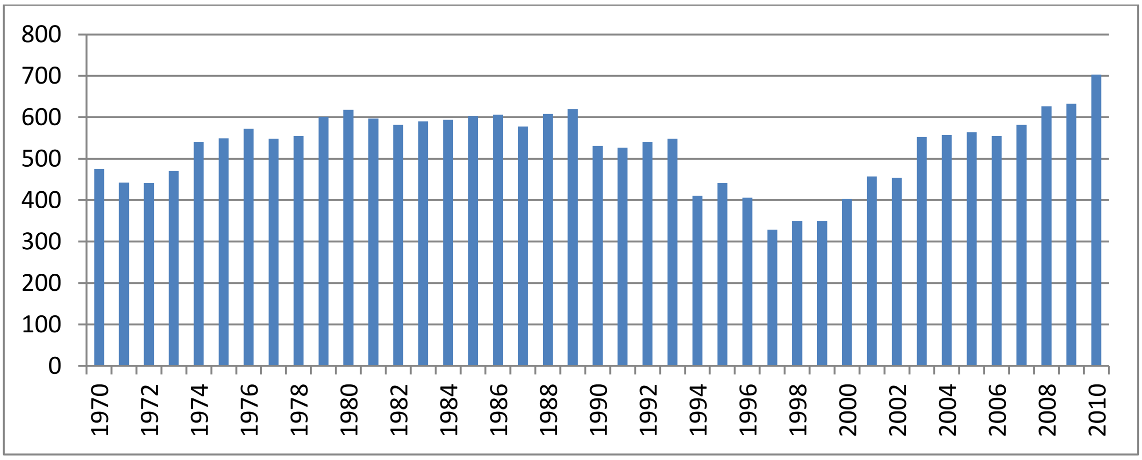


Figure E11 - Transportation: Rail

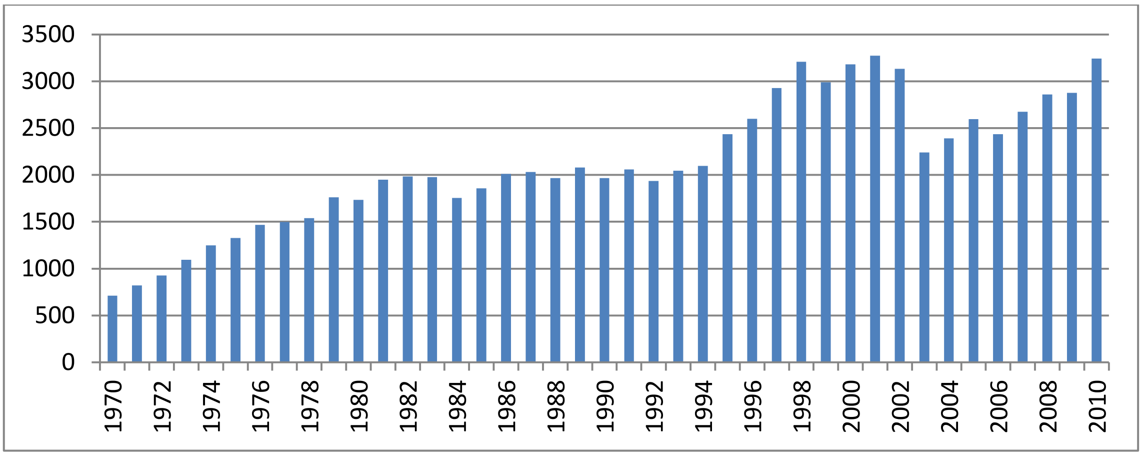


Figure E12 - Transportation: Air

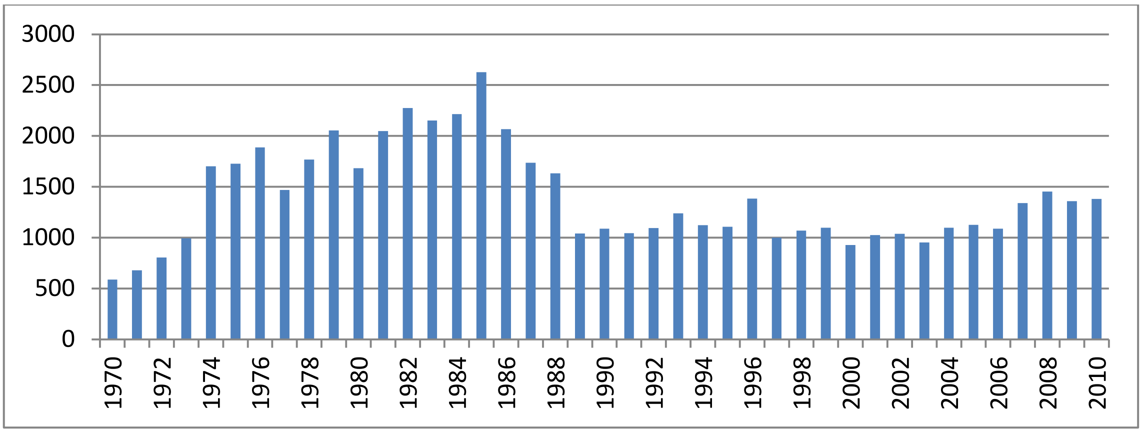


Figure E13 - Transportation: Waterways

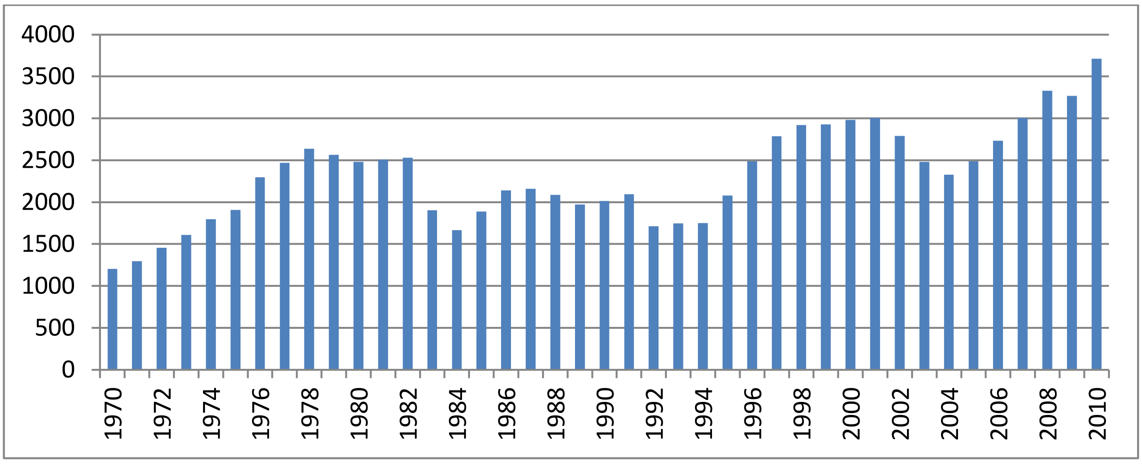


Figure E14 - Industry: Ciment

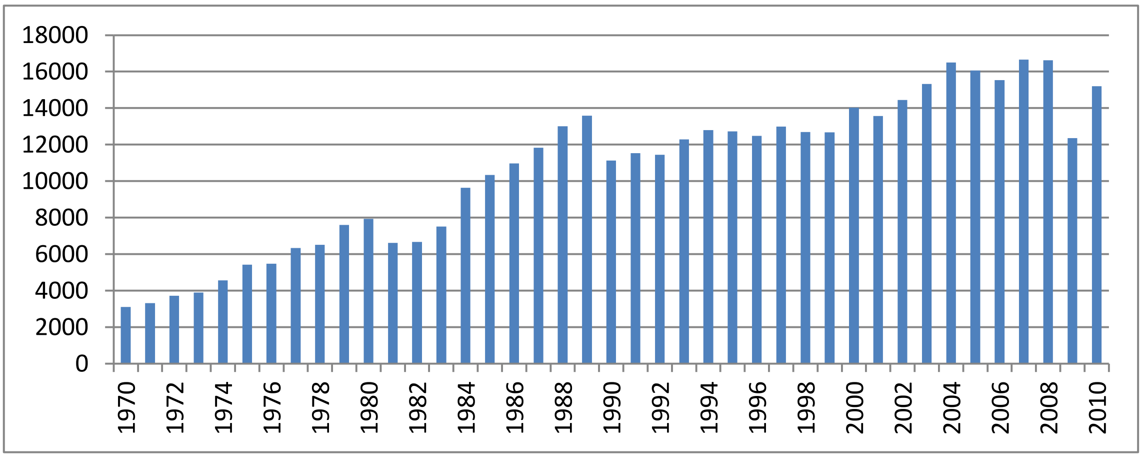


Figure E15 - Industry: Pig-iron and steel

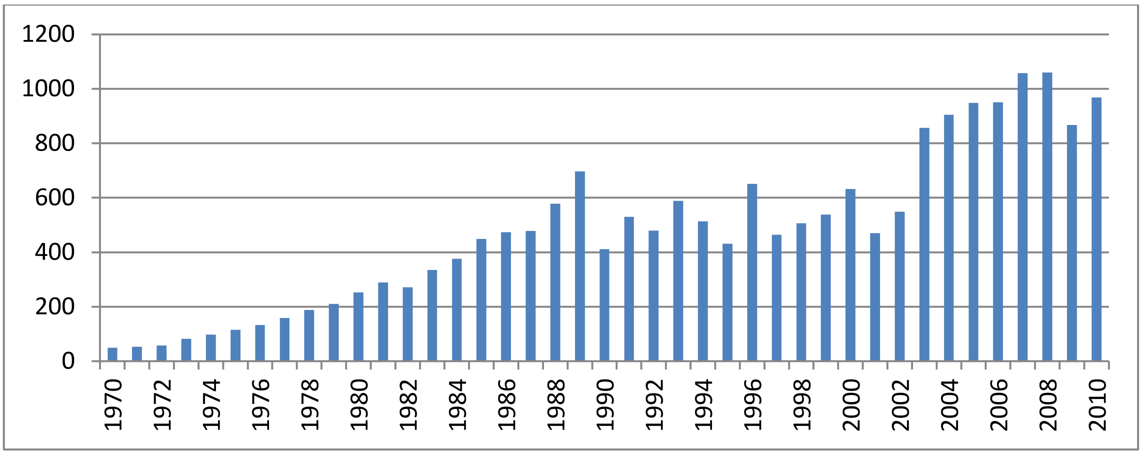


Figure E16 - Industry:Iron-alloys

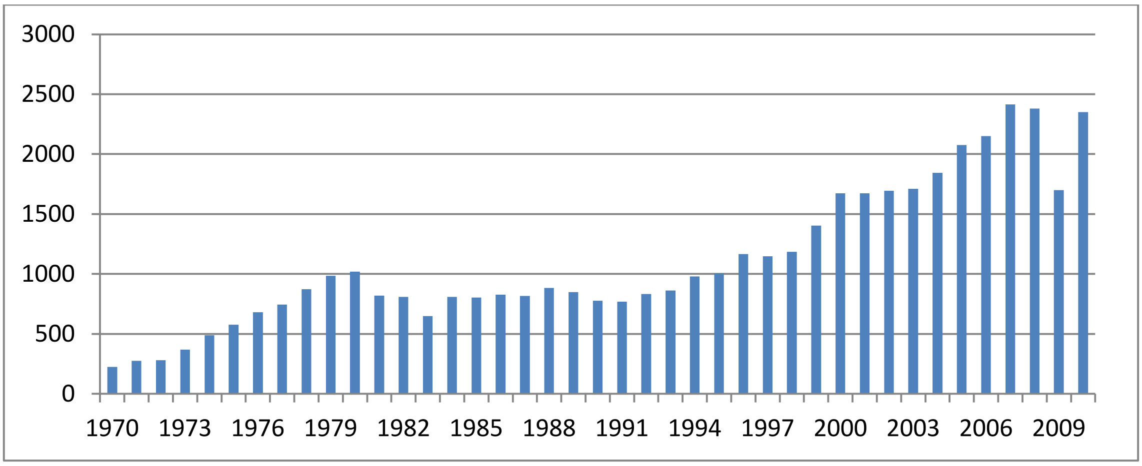


Figure E17 - Industry:Mining and Pelletization

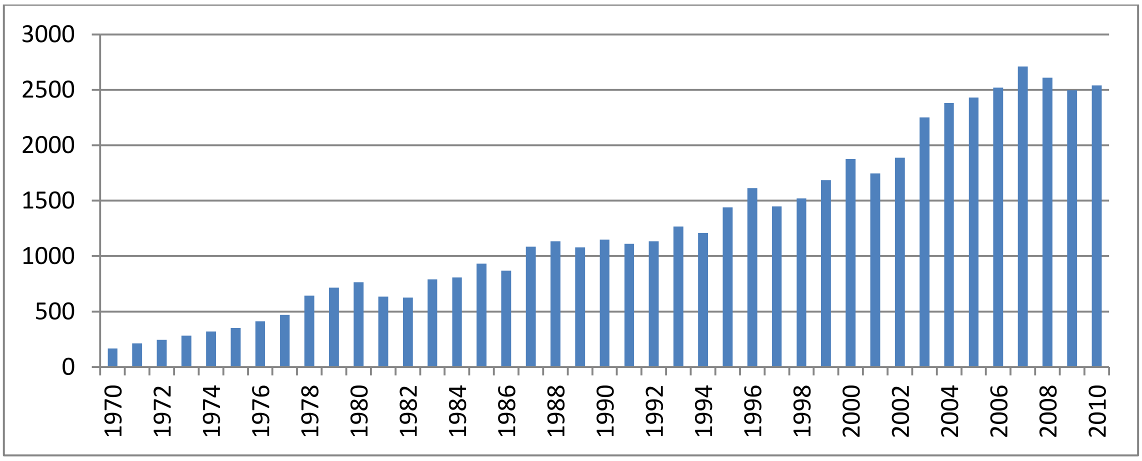


Figure E18 - Industry:Non-ferrous and other metallurgical

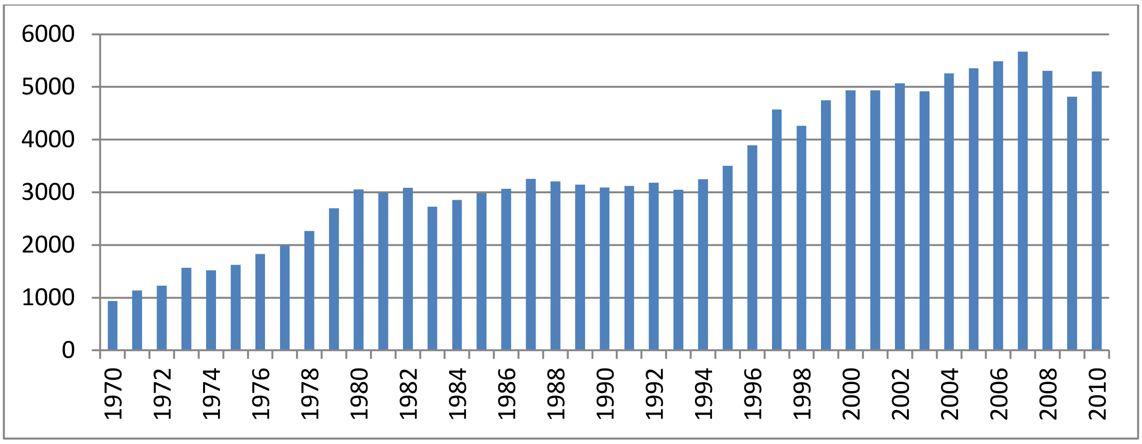


Figure E19 - Industry: Chemical

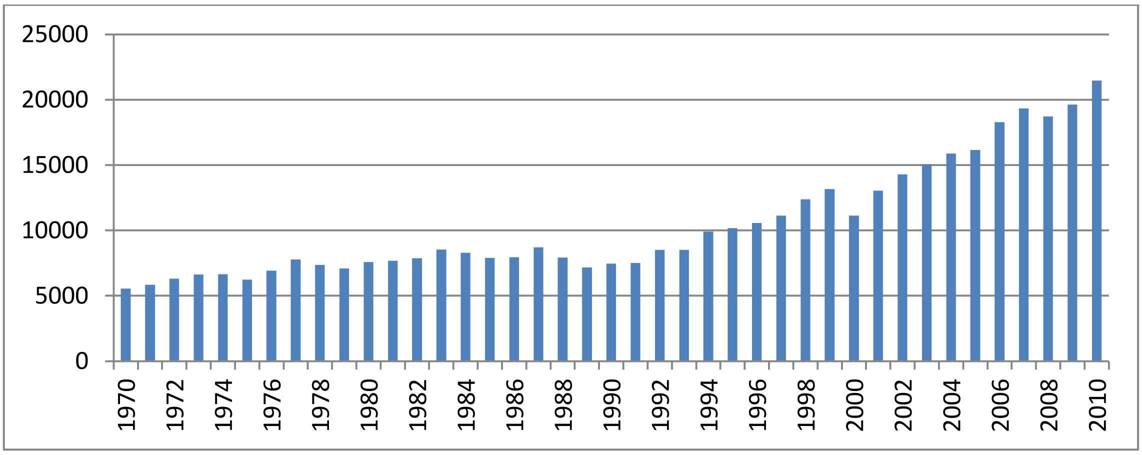


Figure E20 - Food and beverage

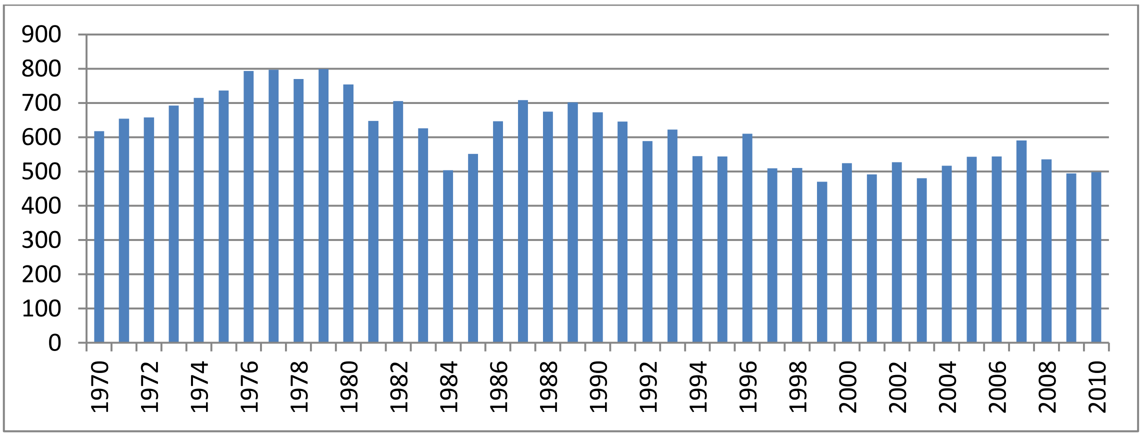


Figure E21 - Textiles

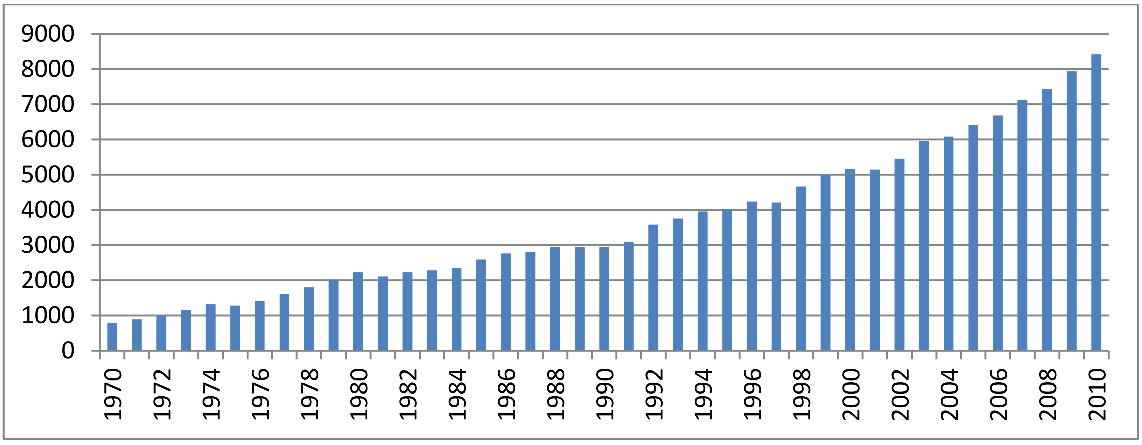


Figure E22 - Pulp and Paper

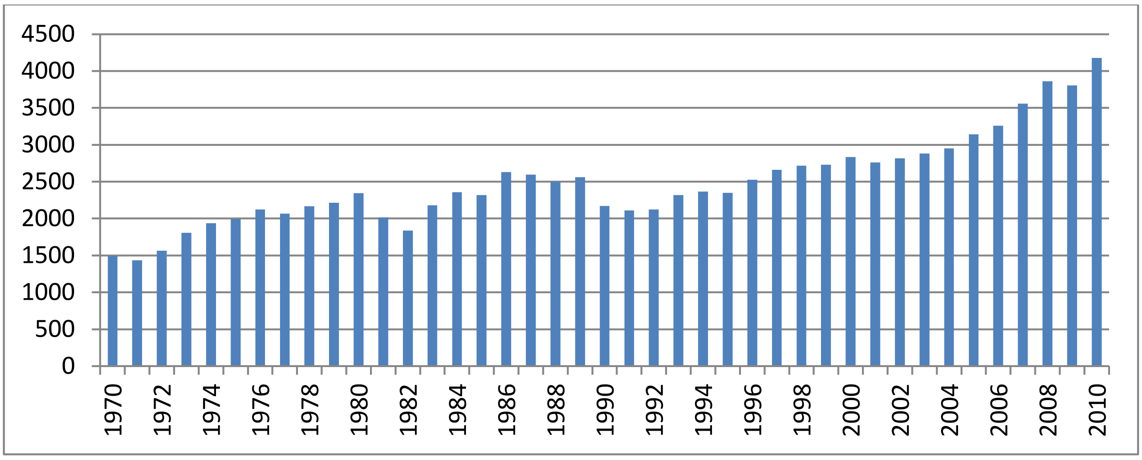


Figure E23 - Ceramics

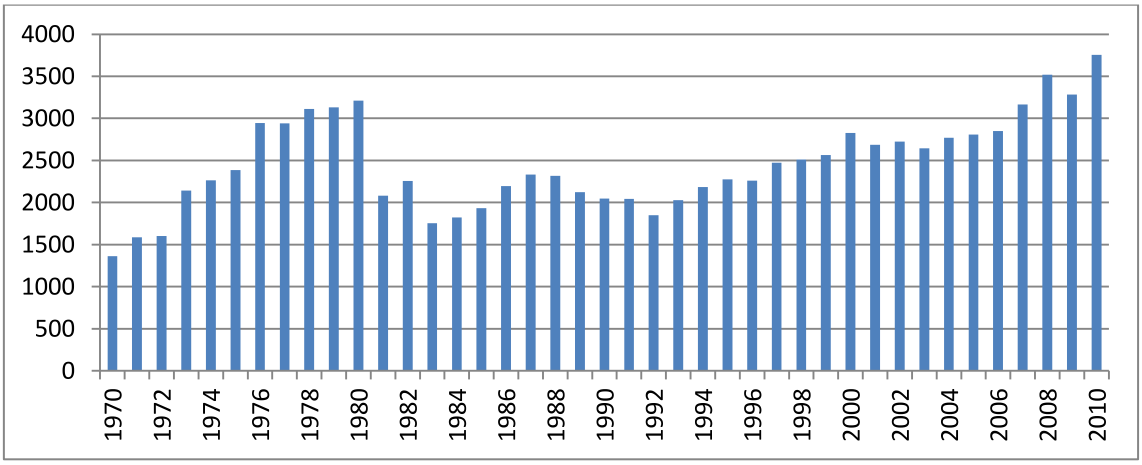


Figure E24 - Other Industrial Sectors

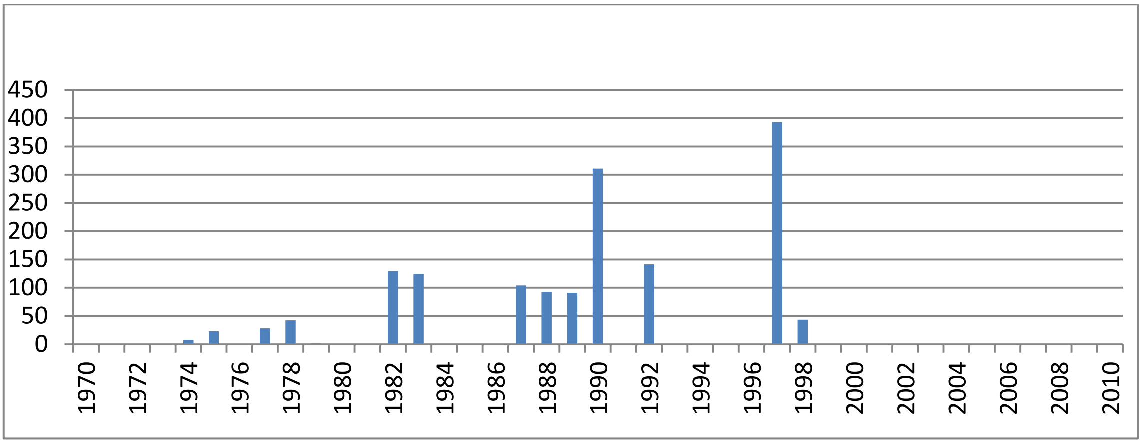


Figure E25 - Unidentified Consumption

APPENDIX F – Fuel Consumption for 1970-2010

Source: Prepared by author, based on BEB (BEN, 2011)

Energy unit : 10^3 toe

Table F1 – Fuel Consumption for 1970-2010

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
1-OIL	0	0	0	0	0	0	0	0	0	0
2-NATURAL GAS	68	92	107	106	264	283	289	415	396	415
3-STEAM COAL	583	613	646	563	573	577	536	742	1175	1120
4-METALLURGICAL COAL	0	0	0	0	0	0	0	0	0	0
5-URANIUM U308	0	0	0	0	0	0	0	0	0	0
6-HYDRAULIC ENERGY	3422	3714	4357	4977	5646	6214	7128	8036	8833	10022
7-FIREWOOD	31852	31807	32143	31897	32599	33154	31882	30822	29794	30375
8-SUGAR-CANE PRODUCTS	3238	3480	3901	4266	4262	3843	4375	5716	5942	6483
9-OTHER PRIMARY SOURCES	223	233	301	311	349	363	412	470	554	808
10-DIESEL OIL	5585	6137	7011	8326	9215	10284	11828	12694	13858	15089
11-FUEL OIL	7582	9103	9404	11625	12840	13617	15487	15790	17206	17859
12-GASOLINE	7446	8103	9076	10645	11029	11268	11348	10315	10531	10478
13-LPG	1367	1475	1631	1809	1927	2016	2210	2327	2578	2847
14-NAPHTHA	0	0	55	52	52	52	16	36	45	30
15-KEROSENE	1131	1223	1346	1550	1659	1734	1900	1951	1986	2233
16-GAS COKE	132	135	137	144	159	173	191	199	212	224
17-COAL COKE	1182	1164	1255	1283	1309	1602	1873	2475	2675	3060
18-URANIUM CONTAINED IN UO2	0	0	0	0	0	0	0	0	0	0
19-ELECTRICITY	0	0	0	0	0	0	0	0	0	0
20-CHARCOAL	1590	1811	2099	2227	2777	3321	3013	3063	3135	3691
21-ANHYDROUS AND HYDRATED ETHYL ALCOHOL	98	136	209	165	101	86	92	341	804	1193
22-OTHER OIL SECONDARY	227	529	502	619	978	973	1148	1254	1639	1997
23-NON-ENERGY OIL BY-PRODUTS	0	0	0	0	0	0	0	0	0	0
24-BITUMEN	278	288	307	345	331	410	526	658	653	739
TOTAL FUEL CONSUMPTION PER YEAR	66003	70042	74490	80911	86071	89970	94254	97304	102015	108661

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
1-OIL	0	0	0	0	0	0	0	0	0	0
2-NATURAL GAS	485	508	707	825	1009	1400	1690	1931	1945	2026
3-STEAM COAL	1220	1829	2236	2207	2241	2510	2987	2750	2293	2265
4-METALLURGICAL COAL	0	0	0	0	0	0	0	0	0	0
5-URANIUM U308	0	0	1176	0	0	0	0	829	360	0
6-HYDRAULIC ENERGY	11082	11241	12132	13022	14321	15334	15682	15955	17115	17596
7-FIREWOOD	31083	30415	29109	30233	33340	32925	32766	32777	32565	32953
8-SUGAR-CANE PRODUCTS	7021	7587	8606	10407	11094	12106	11216	13338	12206	11779
9-OTHER PRIMARY SOURCES	987	1063	1142	1167	1382	1530	1738	1855	1996	1947
10-DIESEL OIL	16070	15914	16256	15948	16485	17502	19589	20672	21250	21863
11-FUEL OIL	17240	13954	12919	10328	9049	9442	11124	11155	11161	10526
12-GASOLINE	8860	8483	8083	6910	6200	6099	6875	5994	5871	6591
13-LPG	3043	3269	3664	3812	3774	4105	4414	4848	5170	5451
14-NAPHTHA	33	46	2	2	12	0	0	0	0	0
15-KEROSENE	2101	2284	2320	2243	2012	2076	2207	2213	2150	2238
16-GAS COKE	227	241	258	273	279	291	306	320	321	311
17-COAL COKE	3197	2662	2860	3378	4440	4941	4946	5545	6255	6169
18-URANIUM CONTAINED IN UO2	0	0	0	0	857	916	37	266	162	473
19-ELECTRICITY	0	0	0	0	0	0	0	0	0	0
20-CHARCOAL	4272	4057	4156	4724	5902	6182	6524	6347	6759	7526
21-ANHYDROUS AND HYDRATED ETHYL ALCOHOL	1422	1321	1932	2677	3443	4235	5584	5686	6024	6507
22-OTHER OIL SECONDARY	1993	1897	1992	2176	2390	2295	2404	2623	2746	2766
23-NON-ENERGY OIL BY-PRODUTS	0	0	0	0	0	0	0	0	0	0
24-BITUMEN	764	668	735	878	1179	1312	1341	1629	1816	1789
TOTAL FUEL CONSUMPTION PER YEAR	111100	107440	110286	111210	119409	125201	131429	136733	138163	140777

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
1-OIL	0	0	0	0	0	0	0	0	0	0
2-NATURAL GAS	2274	2249	2537	2878	2930	3276	4001	4455	4646	5484
3-STEAM COAL	1954	2429	2059	1822	1956	1962	1906	2036	1783	2580
4-METALLURGICAL COAL	0	0	0	174	262	617	1181	1652	1803	2229
5-URANIUM U308	0	1176	0	440	1374	771	0	7320	5085	195
6-HYDRAULIC ENERGY	17770	18722	19200	20208	20864	21827	22847	23982	25056	25188
7-FIREWOOD	28537	26701	25089	24803	24858	23262	21971	21664	21264	22130
8-SUGAR-CANE PRODUCTS	11661	12518	13199	12893	15018	14869	15675	17465	17496	17560
9-OTHER PRIMARY SOURCES	2086	2293	2705	2949	2966	2893	3056	3283	3450	3969
10-DIESEL OIL	21515	22276	22870	23505	24470	26149	27099	28769	30026	31014
11-FUEL OIL	10414	9709	10406	11054	11359	11984	13310	13490	13221	12468
12-GASOLINE	7485	8103	8062	8479	9286	11106	12998	14215	14834	13828
13-LPG	5688	5650	5969	6005	6124	6484	6842	7116	7335	7661
14-NAPHTHA	0	0	0	0	5	30	11	4	4	4
15-KEROSENE	2109	2199	2058	2140	2168	2490	2629	2931	3202	2988
16-GAS COKE	280	271	237	216	141	119	113	108	111	94
17-COAL COKE	5132	6152	6239	6597	6725	6808	6807	6695	6538	5829
18-URANIUM CONTAINED IN UO2	598	406	347	140	22	894	783	1057	1449	1389
19-ELECTRICITY	0	0	0	0	0	0	0	0	0	0
20-CHARCOAL	6137	5402	4961	5256	5333	4915	4554	4379	3986	4401
21-ANHYDROUS AND HYDRATED ETHYL ALCOHOL	5855	6104	5973	6228	6643	6870	7152	6910	6783	6798
22-OTHER OIL SECONDARY	2623	2786	3055	3095	3517	3689	4327	5167	5512	6989
23-NON-ENERGY OIL BY-PRODUTS	0	0	0	0	0	0	0	0	0	0
24-BITUMEN	1467	1603	1694	1758	1678	1698	1605	1569	1524	1454
TOTAL FUEL CONSUMPTION PER YEAR	133584	136750	136659	140642	147698	152714	158868	174269	175105	174253

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1-OIL	0	0	0	0	0	0	0	0	0	0	0
2-NATURAL GAS	7281	9644	12025	12775	15555	16686	17345	17877	21664	17186	23827
3-STEAM COAL	2662	2632	1802	1917	2080	2230	2435	2272	2185	1886	2462
4-METALLURGICAL COAL	2489	2417	2732	2955	3284	3178	3165	3401	3579	2595	3160
5-URANIUM U308	2028	4522	5954	4483	5904	4612	5473	6002	4573	3871	4821
6-HYDRAULIC ENERGY	26168	23028	24594	26283	27589	29021	29997	32165	31782	33528	34680
7-FIREWOOD	23058	22437	23636	25965	28187	28420	28496	28618	29268	24609	26071
8-SUGAR-CANE PRODUCTS	14116	16614	18571	20727	21679	22675	25801	28655	30762	31524	33707
9-OTHER PRIMARY SOURCES	4439	4631	5050	5663	5860	6320	6695	7084	7466	7873	8780
10-DIESEL OIL	31009	32279	32814	32485	34494	34277	34436	36280	39321	38612	43298
11-FUEL OIL	11573	10604	9615	7881	7115	7270	7063	7743	7760	7126	6069
12-GASOLINE	13319	13051	12468	13162	13607	13638	14494	14342	14585	14722	17578
13-LPG	7844	7742	7402	6996	7182	7121	7199	7433	7585	7557	7701
14-NAPHTHA	4	4	4	0	0	0	0	0	0	0	0
15-KEROSENE	3180	3286	3161	2221	2369	2578	2401	2632	2823	2839	3195
16-GAS COKE	85	35	26	1391	1483	1467	1420	1621	1592	1530	1536
17-COAL COKE	6506	6327	6673	6688	6817	6420	6137	6716	6704	5309	6261
18-URANIUM CONTAINED IN UO2	1774	3695	3609	3437	3030	2482	3582	3213	3641	3375	3780
19-ELECTRICITY	0	0	0	0	0	0	0	0	0	0	0
20-CHARCOAL	4814	4409	4615	5432	6353	6248	6085	6247	6224	3979	4648
21-ANHYDROUS AND HYDRATED ETHYL ALCOHOL	5820	5377	6085	5794	6445	6963	6395	8612	11013	11792	12033
22-OTHER OIL SECONDARY	8336	9013	8862	8884	9194	9703	10005	11048	11103	11402	12176
23-NON-ENERGY OIL BY-PRODUTS	0	0	0	0	0	0	0	0	0	0	0
24-BITUMEN	1514	1507	1474	58	76	50	56	61	65	49	114
TOTAL FUEL CONSUMPTION PER YEAR	178019	183254	191172	195197	208304	211360	218680	232024	243694	231364	255895

APPENDIX G – Fuel Consumption Graphs for 1970-2010

Source: Prepared by author, based on BEB (BEN, 2011)

Energy unit : 10^3 toe

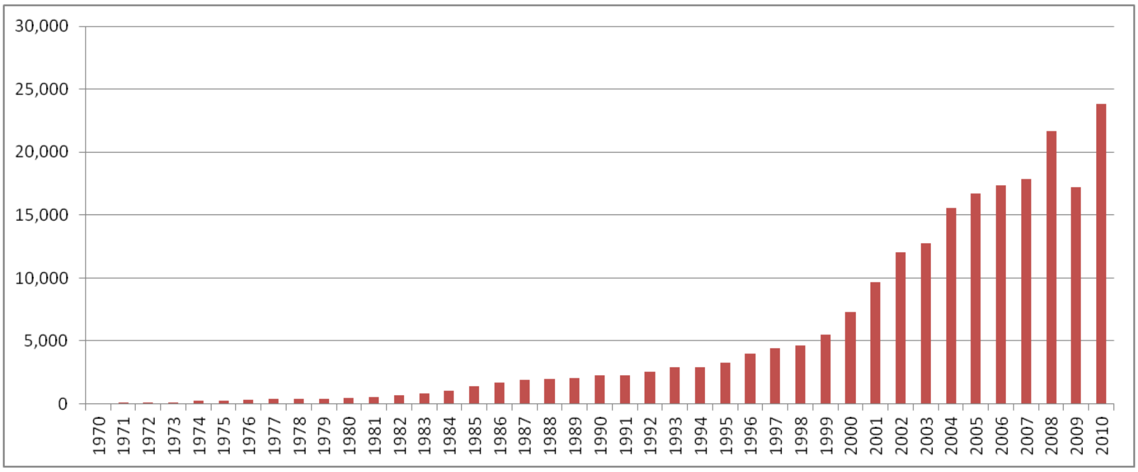


Figure G1– Natural gas

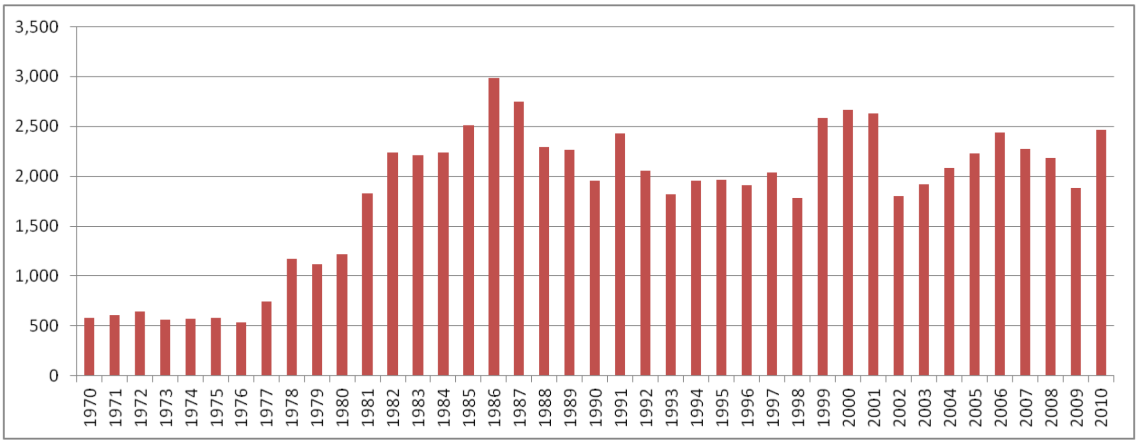


Figure G2 – Steam coal

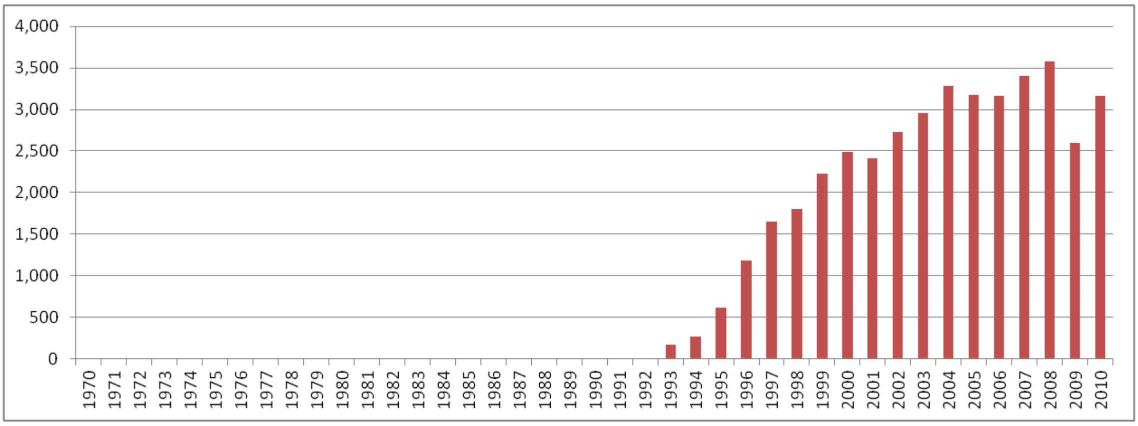


Figure G3 – Metallurgical Coal

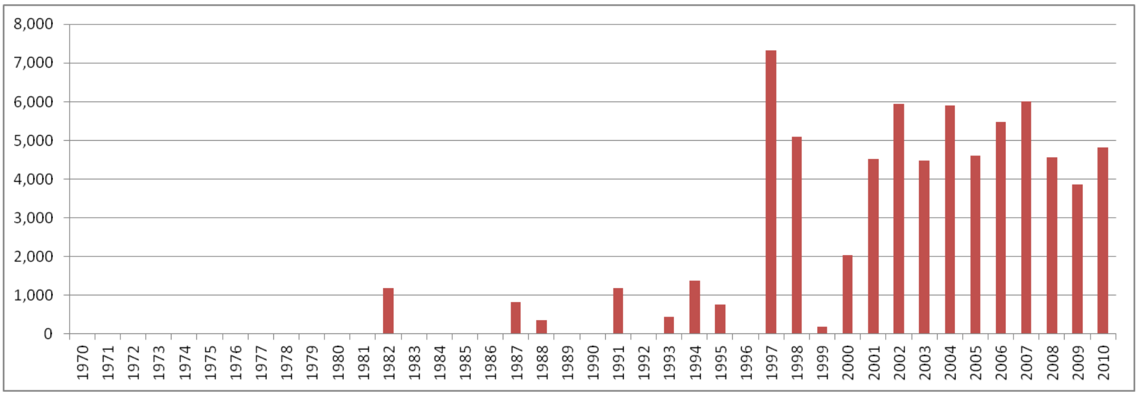


Figure G4 – Uranium U_3O_8

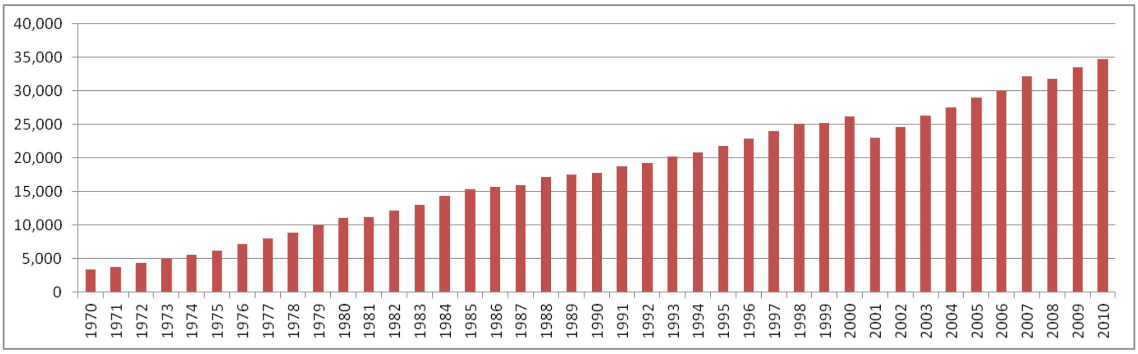


Figure G5 – Hydraulic energy

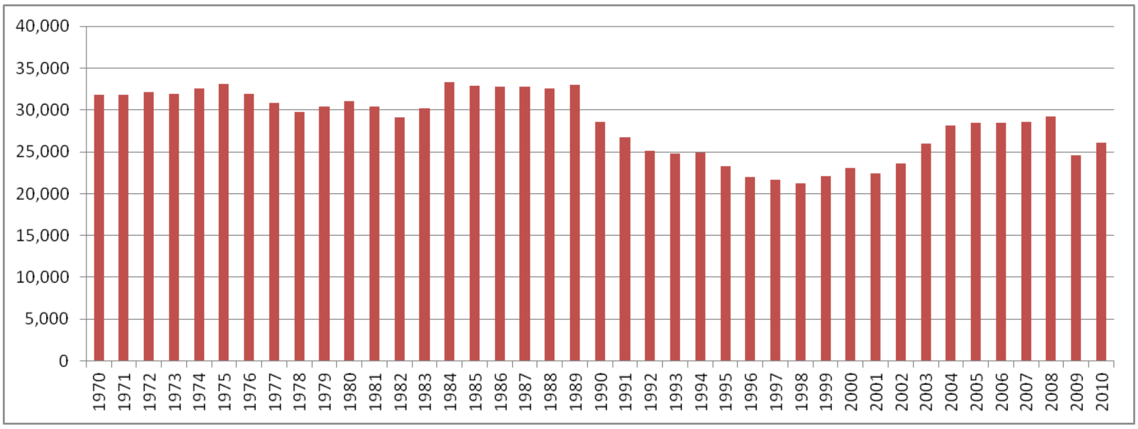


Figure G6 – Firewood

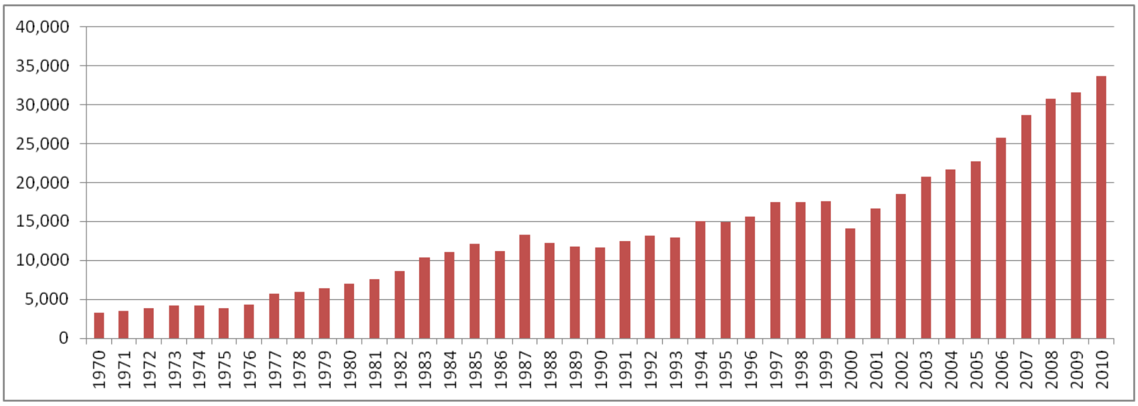


Figure G7 – Sugarcane products

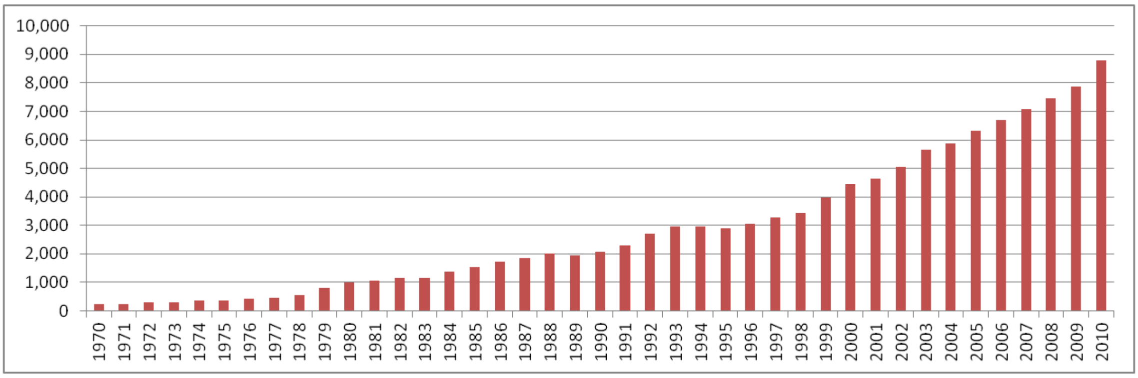


Figure G8 – Other primary sources

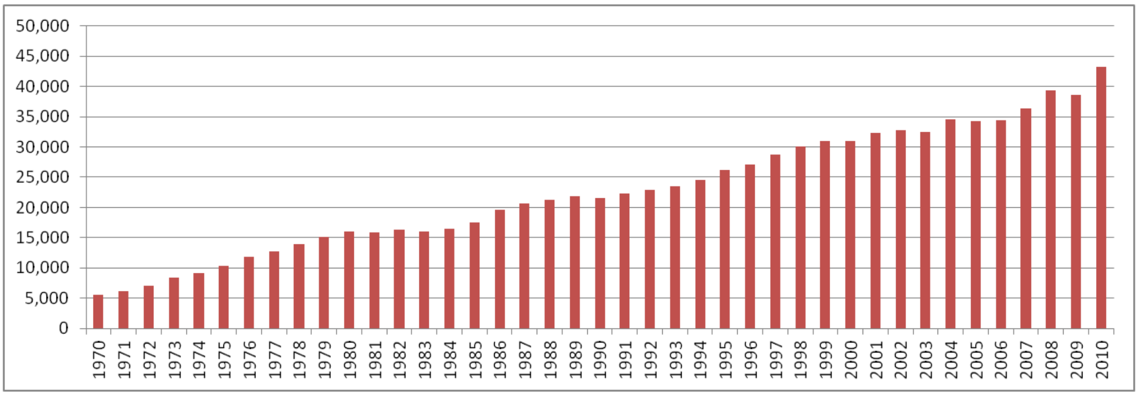


Figure G9 – Diesel oil

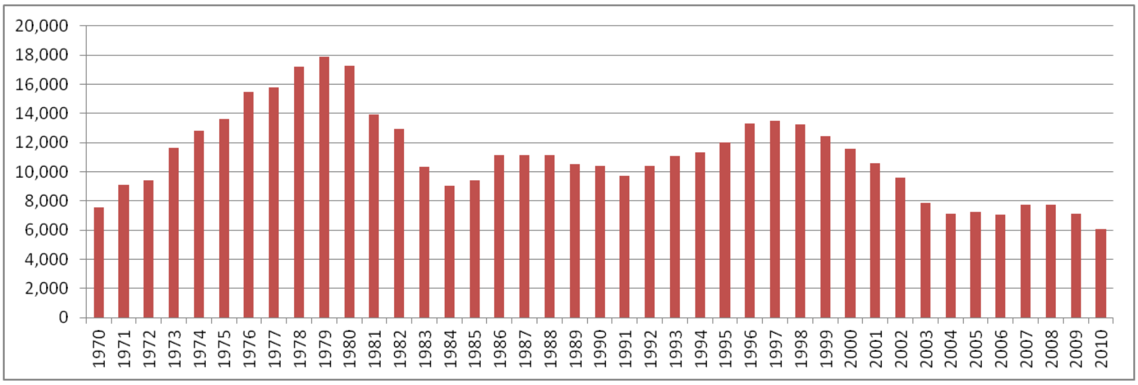


Figure G10 – Fuel oil

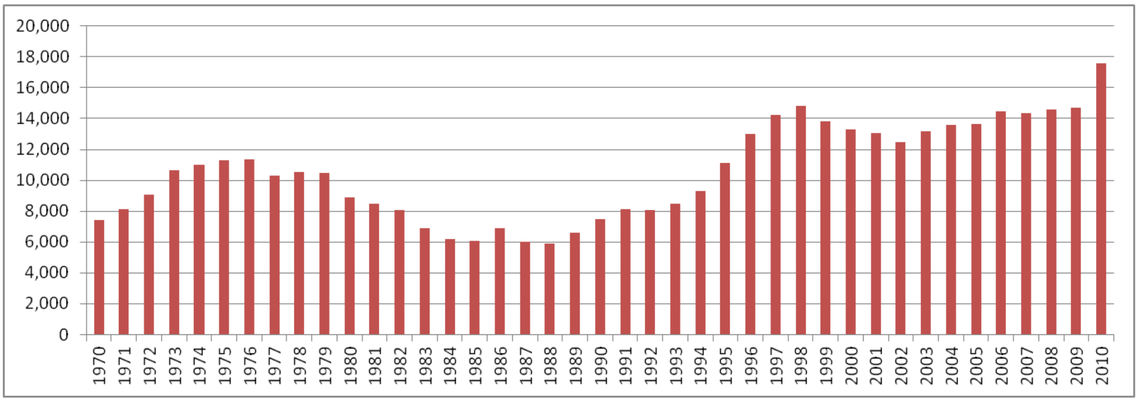


Figure G11 – Gasoline

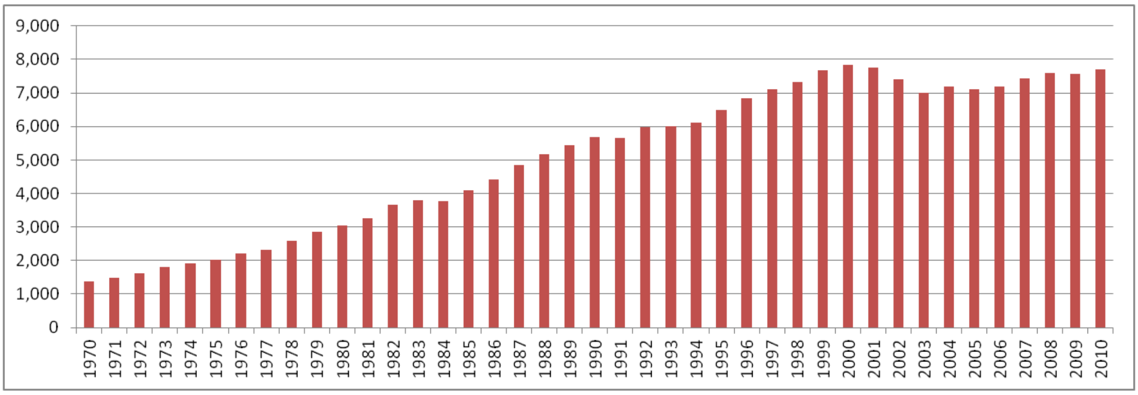


Figure G12 - LPG

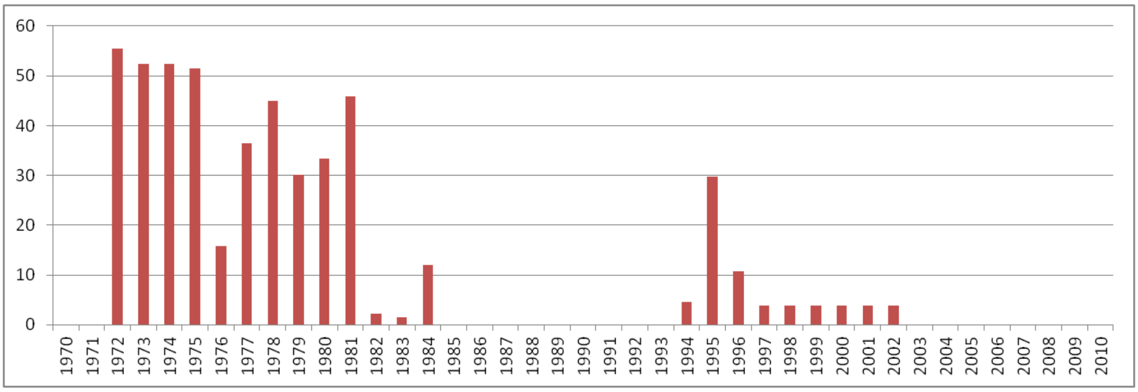


Figure G13 - Naphtha

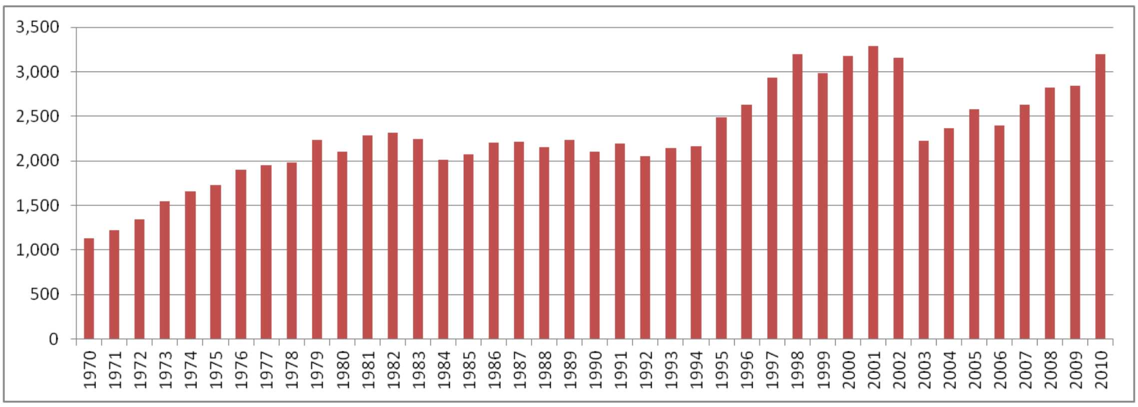


Figure G14 - Kerosene

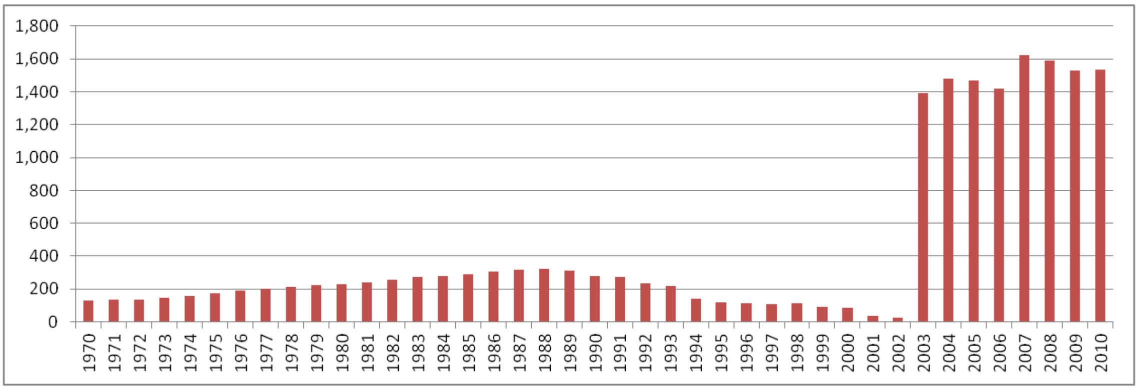


Figure G15 – Gas coke

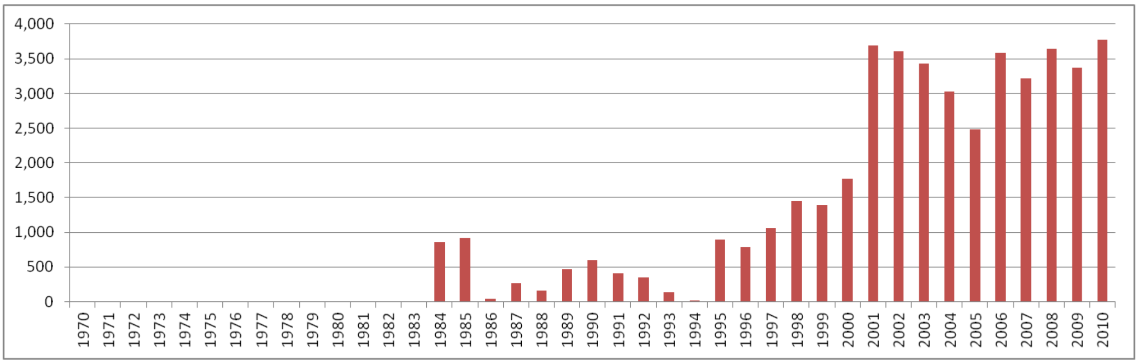


Figure G16 – Uranium contained in UO_2

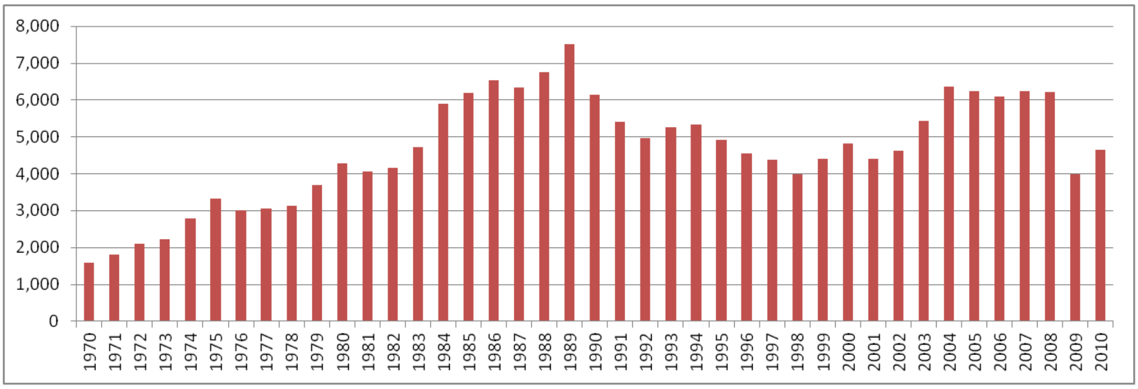


Figure G17 - Charcoal

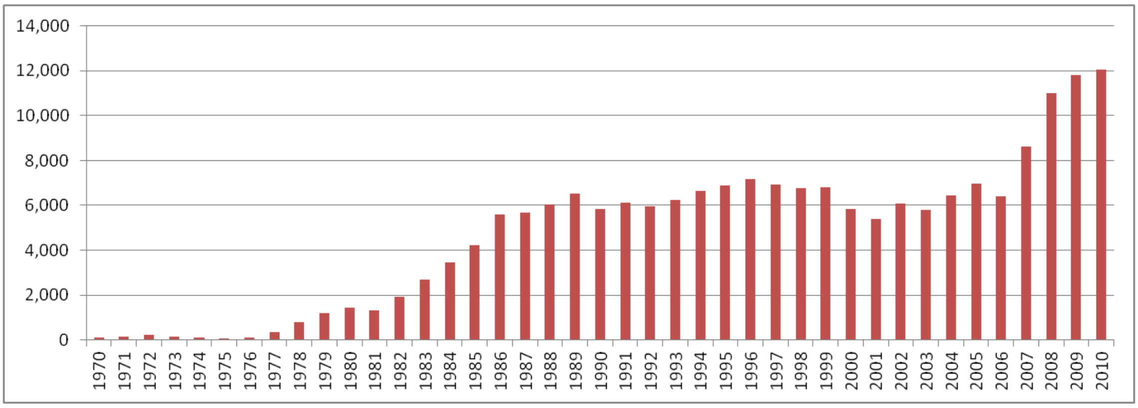


Figure G18 – Anhydrous and hydrated ethyl alcohol

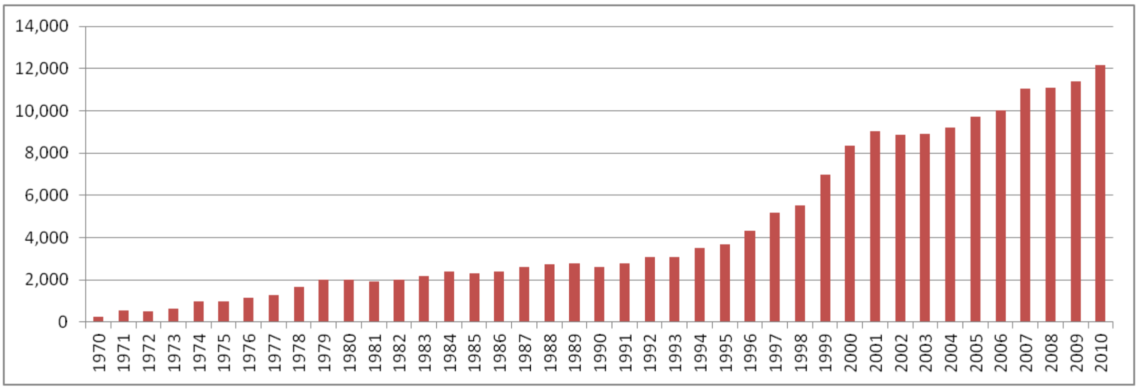


Figure G19 – Other oil secondary

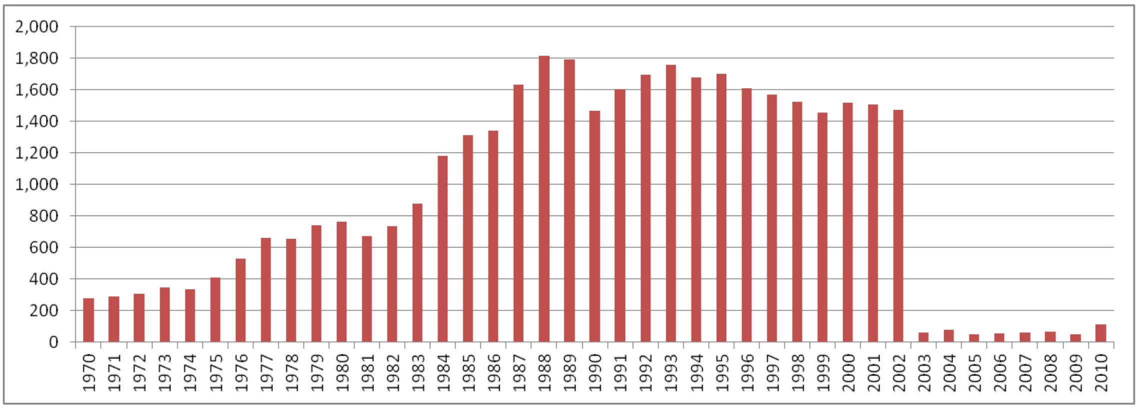


Figure G20 - Bitumen

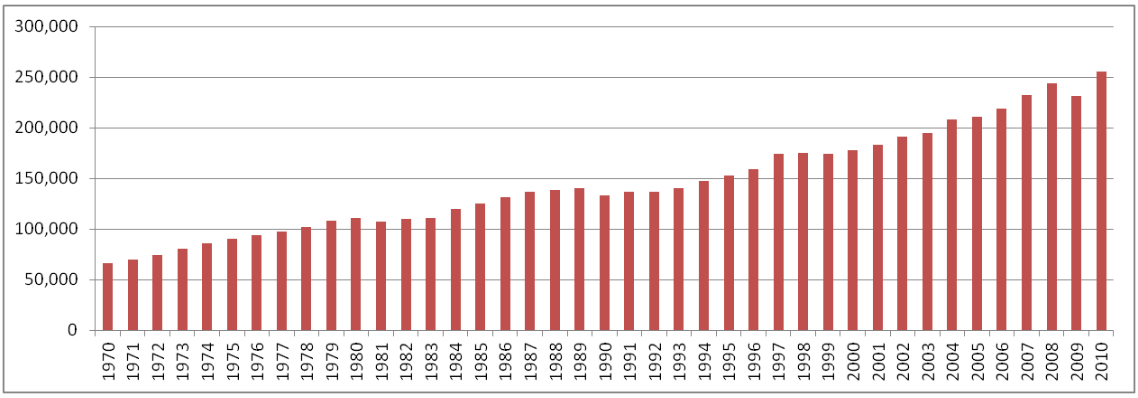


Figure G21 – Total fuel combustion