DEVELOPMENT OF A GLOBAL INTEGRATED ENERGY MODEL TO EVALUATE THE BRAZILIAN ROLE IN CLIMATE CHANGE MITIGATION SCENARIOS

Pedro Rua Rodriguez Rochedo

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.

Orientadores: Alexandre Szklo
Roberto Schaeffer

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"42", Deep Thought – Douglas Adams

"Don't Panic"
− Douglas Adams

“To summarize the summary of the summary: people are a problem.”
− Douglas Adams

“If you put a large switch in some cave somewhere, with a sign on it saying 'End-of-the-World Switch. PLEASE DO NOT TOUCH', the paint wouldn't even have time to dry”
− Terry Pratchett

“You can't go around building a better world for people. Only people can build a better world for people. Otherwise it's just a cage.”
− Terry Pratchett

“Build a man a fire, and he'll be warm for a day. Set a man on fire, and he'll be warm for the rest of his life”
− Terry Pratchett

“If the road is easy, you're likely going the wrong way.”
− Terry Goodkind

“Think of the solution, not the problem”
− Zedd, Terry Goodkind

“Valar Morghulis”
− Arya Stark, George R. R. Martin

“All we have to decide is what to do with the time that is given us” –
− Olórin, J. R. R. Tolkien

“We already came this far. Anyway, we’re gonna save you. And then, if you still want to die, you can die after we save you.”
− Monkey D Luffy, Eiichiro Oda

“Niku”
− Monkey D Luffy, Eiichiro Oda

“People assume that time is a strict progression of cause to effect, but *actually* from a non-linear, non-subjective viewpoint - it's more like a big ball of wibbly wobbly... time-y wimey... stuff.”
The Doctor, Steven Moffat

“Don’t blink!
The Doctor, Steven Moffat

“The very powerful and the very stupid have one thing in common: they don't alter their views to fit the facts; they alter the facts to fit their views.”
The Doctor, Steven Moffat

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À minha mãe e meu pai, por absolutamente tudo. Também às minhas irmãs, Tica e Paula, e meus (não tão mini) sobrinhos, Bezão e Chico.

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Aos colegas do YSSP 2013 no IIASA, espalhados pelo mundo.

Ao Google.

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

DESENVOLVIMENTO DE UM MODELO ENERGÉTICO INTEGRADO GLOBAL PARA AVALIAR O PAPEL BRASILEIRO NOS CENÁRIOS DE MITIGAÇÃO DE MUDANÇAS CLIMÁTICAS

Pedro Rua Rodriguez Rochedo

Agosto/2016

Orientadores: Alexandre Szklo

Roberto Schaeffer

Programa: Planejamento Energético

Apesar do sucesso na determinação do Acordo de Paris, os compromissos individuais (INDC) são considerado insuficientes para limitar o aquecimento global abaixo de 2° C até o final do século. Neste contexto, o principal objetivo deste estudo é investigar o papel que o Brasil pode desempenhar no contexto de estabilização climática no longo prazo. Para isso, um modelo integrado mundial foi desenvolvido para simular os sistemas globais de energia e uso da terra. Ele provê aos especialistas e tomadores de decisão, nos níveis nacional e global, uma ferramenta capaz de gerar as informações necessárias sobre as estratégias de desenvolvimento possíveis e repercussões de cenários climáticos de longo prazo, apoiadas por uma metodologia que está de acordo com a literatura internacional sobre os impactos socioeconômicos e ambientais. Os resultados sugerem que as variáveis globais estão de acordo com a literatura mais recente. Além disso, dependendo do cenário climático, o Brasil pode contar com um orçamento de carbono ainda disponível entre 65 e 225 MtCO2eq. No cenário mais rigoroso, as emissões brasileiras precisam reduzir rapidamente após 2050, atingindo valores negativos por volta de 2,0 GtCO2eq em 2100. Portanto, apesar da aparente convergência da INDC brasileira no sentido de manter o aumento da temperatura média da superfície em torno de 2°C, os resultados deste estudo sugerem que os verdadeiros desafios ainda estão por vir. Eventualmente, Brasil terá de enfrentar a necessidade de manter as emissões de GEE em cheque, simultaneamente permitindo o crescimento econômico e desenvolvimento social.

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

DEVELOPMENT OF A GLOBAL INTEGRATED ENERGY MODEL TO EVALUATE THE BRAZILIAN ROLE IN CLIMATE CHANGE SCENARIOS

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August/2016

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Despite the major accomplishment in the development of the Paris Agreement, the individual pledges (INDC) are considered insufficient to limit global warming to below 2°C by the end of the century. In this context, the main objective of this study is to investigate the role Brazil can play in long-term global climate stabilization context. As such, a global integrated model was developed to simulate the global energy and land systems. This model provides experts and decision makers at the national and global levels the necessary tool for possible development of strategies and the repercussions of long-term climate mitigation scenarios, supported by assessments in accordance to the international literature on the impacts of socioeconomic backgrounds and their environmental impacts. Findings suggest that global variables are in agreement if the most recent literature. Depending on the global climate target, Brazil can count on a remaining carbon budget between 65 and 225 MtCO2eq. At the most stringent scenario, the Brazilian emissions need to plunge rapidly after 2050, achieving negative values of about 2.0 GtCO2eq by 2100. Hence, despite the apparent good agreement of the Brazilian INDC towards keeping the increase of mean surface temperature to about 2°C, the findings of this study suggest that the true challenges are still to come. Brazil will need to face the need to keep its GHG emissions in check, whilst still allowing for economic growth and social development.

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ACRONYSMS

AEZ – Agro Ecological Zones

AGR – Agriculture Sector

AFOLU – Agriculture, Forestry and Other Land Use

APWR – Advanced Pressurized Water Reactor

BAL – Trade Balance

BECCS – Bioenergy with carbon capture and storage

BIOCCS – Bioenergy with carbon capture and storage

BOF – Blast Oxygen Furnace

BRICS – Brazil, Russia, India, China and South Africa

BTH – Biomass to Hydrogen

BTL – Biomass To Liquids

BWR – Boiling Water Reactor

CAESAR – Carbon and Energy Strategies Analysis for Refineries

CAP – Capital Formation

CCS – Carbon Capture and Storage

CDD – Cooling Degree Days

CGE – Computable General Equilibrium

CH4 – Methane

CO2 – Carbon Dioxide

CO2eq – Carbon Dioxide Equivalent

COP – Conference of Parties

CSP – Concentrated Solar Power

CTH – Coal to Hydrogen

CTL – Coal to Liquids

EAF – Electric Arc Furnace

EMF – Energy Modelling Forum

EOR – Enhanced Oil Recovery

FAEE – Fatty Acid Ethyl Esther

FAME – Fatty Acid Methyl Esther

FBR – Fast Breeder Reactor

GCR – Gas Cooled Reactor

GDP – Gross Domestic Product

GHG – Geenhouse Gases

GIS – Geographic Information System

GVE – Government Expenditure

HDD – Heating Degree Days

HDT – Heavy Duty Truck

HHE – Household Enpenditure

HHV – Higher Heating Value

HTGR – High Temperature Gas Reactor

HVAC – Heating,Ventilation and Air Conditioning

IAM – Integrated Assessmen Model

IEA – International Energy Agency

IGCC – Integrated Gasification Combined CYcle

IND – Industry sector

INDC – Intended Nationally Determined Contribuition

IPCC – Intergovernmental Pannel on Climate Change

LDV – Light Duty Vehicle

LED – Light Emitting Diode

LHV – Lower Heating Value

LPG – Liquified Petroleum Gas

LULUCF – Land Use, Land Use Change and Forestry

LWGR – Light Water Graphite Reactor

MAGICC - Model for the Assessment of Greenhouse-gas Induced Climate Change

MESSAGE – Model for Energy Supply Systems And their General Environmental impact

MSW – Municipal Solid Waste

N2O – Nitrous Oxide

NGCC – Natural Gas Combined Cycle

OECD – Organisation for Economic Co-operation and Development

PC – Pulverized Coal

PI – Production Index

PHWR – Pressurized Heavy-Water Reactor

PKM – Passanger Kilometer

PV – Photovoltaics

PWR – Pressurized Water Reactor

RCP – Representative Concentration Pathways

SER – Services sector

SRES – Special Report on Emissions Scenarios

SSP – Shared Socioeconomic Pathways

ST – Steam Turbine

TDM – Tonne of dry matter

TKM – Tonne Kilometer

UNFCC – United Nations Framework Convention on Climate Change

UO2 – Uranim dioxide

1. Introduction

1.1. Background

Anthropogenic greenhouse gas (GHG) emissions have largely increased since the pre-industrial era, causing an increase in the atmospheric concentration of GHG. This man-made disturbance in the environment is extremely likely to have been the dominant cause of the observed warming since the mid-20th century (IPCC, 2014).

Climate change is one of the major global policy challenges of our time (KRIEGLER *et al.*, 2015; RIAHI *et al.*, 2015). In recent years, studies have gathered an overwhelming amount of evidence that have shown the effects of climate change, most comprehensively in natural systems, and the human influence on the climate system (IPCC, 2014). At the same time, slow progress in international climate negotiations has given rise to scepticism about the prospect of global cooperative action on climate change (KRIEGLER *et al.*, 2015).

At the Paris Conference (COP21, or 2015 United Nations Climate Change Conference), the relevance of this issue at a global scale became more evident, since it officially acknowledges climate change as “an urgent and potentially irreversible threat to human societies and the planet” (UNFCC, 2015). The Paris Agreement, signed in COP21 by 195 countries, establishes the objective of holding the increase in the global average temperature to well below 2 °C above pre-industrial levels.

The individual contributions of each country within the Agreement in order to achieve the global target are determined by all countries individually and named "Intended Nationally Determined Contributions" (INDC). The agreement also requires that the countries indicate "ambitious" contributions that "aims for achieving the objective of this agreement." The contributions should be announced every five years and must be registered with the Secretariat of the United Nations Framework for Climate Change, or UNFCCC (UNFCCC, 2015).

Despite the major effort in the development of the Paris Agreement, the specific targets for global and national levels have not been clearly defined by the UNFCC. Additionally, all intended national contributions should conform towards the global target.

However, there is a potential difficulty in accounting for all individual contributions, which have a tendency to be prepared in a short-sighted and individualistic

manner. Thus, there is a high probability that there is a problem of additionality within the contributions.

Moreover, the main issue is that national governments are addressing climate change in the context of their national priorities, such as energy security, alleviation of poverty and the challenge of decoupling GHG emissions from typically "fossil fuel dependent" sectors in emerging economies (e.g. Russia, China and Brazil). In nearly all countries the most important driving forces for climate policy are not solely the concern about climate change (IPCC,2014).

Therefore, there is a high probability that in accounting for all intended national contributions, which could be developed in a short-sighted and protectionist approach by the individual countries, the global target is not achieved.

In fact, ROGELJ *et al.* (2016) have assessed the role of the INDC for achieving the target of the Paris Agreement. The findings show that additional actions are required to maintain a reasonable chance of meeting the target of keeping warming well below 2 degrees Celsius, whilst acknowledging that the INDCs are a historic achievement. Not only for the engagement shown by both decision-makers and non-state actors (businesses, citizens and civil organizations), but also for the effective reduction of GHG emissions and the multiple socio-economic benefits it brings.

Considering only the mean values of the study, the INDC could reduce the global GHG emissions in 2030 from 59 GtCO2eq/year to about 55 GtCO2eq/year. Meanwhile, the least cost projections for achieving the 2°C increase is related to GHG emissions in 2030 of about 42 GtCO2eq/year. Therefore, the challenge to limit warming to below 2 °C from current INDC levels beyond 2030 is daunting, and additional efforts have to be made. In regards to global temperature rise, the study also estimates that, at the best case, the implementation of all INDC would achieve an increase of 3.9°C by 2100 with a 90% probability (ROGELJ *et al.*, 2016).

In the national context, the Brazilian Government submitted its INDC at COP21. The Brazilian INDC (Brazil, 2015) establishes absolute emissions targets of 1.3 GtCO2eq by 2025 and an indication of 1.2 GtCO2eq by 2030[1]. Despite establishing some targets in Energy, Agriculture and Land Use, Land Use Change and Forestry (LULUCF), the INDC is rather vague in detailing how these goals are to be achieved.

[1] These value correspond to reductions of 37% and 43%, respectively, compared to GHG emissions in2005.

The land use emissions indications in the INDC have elicited criticism from observers saying that although relatively ambitious, they do not go far enough, especially in light of the potential for mitigation in Brazil. For the Energy sector[2], studies show that most of INDC targets related to the energy system are feasible at relatively low-carbon-implicit prices (KOBERLE *et al.*, 2015).

Moreover, the balance between effort (costs, barriers and regulatory issues) and benefits from GHG reductions and sustainable developments from both AFOLU (Agriculture, Forestry and Land Use) and Energy sectors could be weighted. In other words, should more be done to abate emissions from one sector, less will be required from the other, in order for the country to meet its INDC targets. Although AFOLU mitigation measures tend to bring the most co-benefits, including a higher net present value, there are important barriers that may stand in the way such as transaction costs (KOBERLE *et al.*, 2015).

Despite indicating net reduction in GHG emissions by 2030, which must be accounted for as a significant effort from the Brazilian government, the Brazilian INDC was determined "within boarders", meaning that it only establishes targets and contribution within the country, which can still be driven by governance protectionism towards its economy and market competitiveness.

This individualistic approach is quite contradictory since, on one side, it disregards the potential role Brazil can play in the climate agreement as owner of the largest forested area in the world, as a major agricultural producer and a possible major exporter of bioenergy commodities. On the other hand, the country's petroleum production is increasing and chances are that Brazil will export more than 2 Mbpd in the next ten years, achieving a new role as one of the top five petroleum producer between almost 20-30 years (SARAIVA *et al.*, 2014; ROCHEDO *et al.*, 2016)

In this context, the true contribution Brazil could actually provide towards holding the UNFCC target of well below 2°C is, in a broader sense, underrated and, more importantly, undervalued. Also, this refers again to the fact that the INDC is most likely under achieving towards more ambitious long term climate goals.

[2] Including energy-related emissions from energy, transportation, industry, households, services, agricultural sectors, and emissions from urban residues and industrial processes.

1.2. Objectives

Thus, the main objective of this study is to investigate the role Brazil can play in the long term global climate stabilization context. This includes not only the assessment of national GHG emissions, but also the possibilities for new markets and mitigation options.

As such, this study aims to develop a mathematical tool commonly called an integrated assessment model (IAM), to simulate the world energy system (instead of only the Brazilian system). This type of model is nearly unprecedented in terms of non-OECD countries and is currently being developed in Brazil, India and China. Still, it is important to note that the development of a global modelling tool from a Brazilian perspective will help the scientific community as a whole, but especially national research institutions, which are undergoing climate change studies.

This is the only effective way to evaluate global scenarios associated with the role that the country can take in relation to GHG mitigation - i.e. evaluate a carbon budget for the country.

At this point, it should also be noted that the development of a global optimization model is an unprecedented effort of the Brazilian scientific community, which will provide a consistent framework as described by the international research community.

Finally, another major relevance of this work relies in its capacity to provide experts and decision makers at the national and global levels the necessary information on possible development strategies and repercussions of long term climate scenarios. Thus, Brazil can strengthen its position and become even more active in the climate negotiations, for it will be supported by assessments in accordance to international literature on the impacts of socioeconomic background and its environmental impact.

1.3. Challenges for the energy transition

A step of great importance for the stabilization of the climate process is the energy transition to a low carbon economy. Changes in energy technologies and the structure of economies should create the opportunity to definitively disassociate economic growth and the increase in GHG emissions.

According to IEA (2015), global energy intensity and global primary energy carbon intensity must be reduced by around 60% by 2050 compared to 2013, to achieve stabilization under 2°C. This implies that the annual rate of reduction in global energy intensity is expected to be of 2.6% per annum until 2050. This represents a significant acceleration in the current behaviour, with an average of 1.1% until 2050 (IEA, 2015).

Innovation and technology development are crucial to meet the objectives of climate change, taking into account also major issues such as economic and energy security. However, to create a favourable environment for technological development and energy transition, governments must define their objectives and provide stable condition and full support throughout all stages of the energy transition.

UNRUH (2000) argues that the world's economies have become hostages of technologies based on fossil fuels through a process driven by technological and institutional pursuit for increasing returns to scale. This condition, known in the literature as carbon lock-in, arises from the combination of systematic forces that perpetuate the infrastructure based on fossil fuels, despite their known environmental externalities.

Several studies, such as the IEA (2015) and MCGLADE AND EKINS (2015) suggest that even in long-term scenarios fossil fuels maintain a consistent participation in the global energy matrix. Even in scenarios with the goal of climate stabilization at up to 2 ° C, it is still possible to verify the persistence of certain fossil fuels, but with a relatively much lower than the trend participation.

Thus, the transition to a global low carbon energy system will require a change to an alternative technology system in the long run (BARRETO AND KEMP, 2008). The mechanisms and driving forces for technological development, as well as the characteristics of the prevailing and emerging schemes, must be understood so that the necessary actions to stimulate change in the desired direction are taken (BARRETO AND KEMP, 2008).

Given the important role of technology, the appropriate incorporation of mechanisms of technological diffusion models to energy is an important research topic. BARRETO AND KEMP (2008) argue that this fact requires two actions: the technological diffusion models should be improved in order to reflect the determinants key diffusion of energy technologies and, on the other hand, these improved models should be incorporated into energy models.

For GRUBLER (2012), there is an urgent need for the next energy transition, as the current energy systems are unsustainable in relation to social, economic and

environmental aspects. About two billion people remain excluded from the benefits of past energy transitions, which improved and eased access to modern and "clean" energy services, either industrial, residential or transportation (GRUBLER, 2012).

According to NEUVONEN *et al.* (2014), despite the changes in large industrial systems and infrastructure presenting a higher emission reduction potential, the future of lifestyles and consumer choices should be explored in the context of a low-carbon future. Firstly, because over the years, the transitions in terms of technology, economy, laws and values led to changes in lifestyle. Moreover, the adoption of new technologies and advances in politics depends on social structures and changes in behaviour.

Thus, the energy system faces a great challenge in order to allow the pursuit of climate change mitigation, especially for more stringent scenarios. As such, the model and assessment developed in this study will provide insights on how the future of the energy system can be compatible with limiting climate change.

1.4. Thesis outline

Regarding its structure, this work is divided into eight chapters. This, the first chapter, presents the major outline and the structure of the remainder of the study. The second chapter introduces all relevant concepts, definitions and presents the the literature review.

In the third chapter, the methodology used and the estructure of the model is presented. The fourth chapter presentes the estimates for energy resources, though a massive review of literature data and even some unpredented results. Then, in the fifth chapter, the macroeconomic scenario considered in this assessment is presented, as well as the development of all major sector in terms of energy service demands. The sixth chapter focuses on the land system and the agriculture sector.

The seventh chapter presents the results and provides a basic discussion of the major findings. Finally, the eighth chapter provides the final remarks, including the overall findings of this study and suggestion of future complimentary studies.

2. Definitions and Background for Integrated Assessment

The development of long-term scenarios of social and environmental systems is an important tool to assess the risk of global climate change (VAN VUUREN *et al.*, 2012). Through the definitions of a limited number of assumptions, scenario development can be an important tool for assessing the dependency and robustness of future conditions to those assumptions.

This procedure is especially important in the context of climate change, for it is a long-term process, whose consequences are not easily perceived in the short-term. In fact, it is a problem where decision made today will definitely have repercussion for decades.

One of the great advantages of using scenarios is to assess systematically the impact of the inherent uncertainties concerning the development of key variables. Integrated assessment models (IAM) usually deal with large uncertainties, such as climate sensitivity, socioeconomic and technological development, among others. The determination of clear assumptions about the evolution of these parameters in time is critical to make the result analysis in a consistent manner.

Therefore, scenario development and assessment allows the analysis of highly complex systems, as it allows analysing a limited number of possible future conditions, especially regarding the future state of socio-economic variables such as energy, land use, and greenhouse gas emissions (HENRICHS *et al.*, 2010).

Finally, this brief introduction to the subject discloses the need to work with scenarios within the same context, so that the evaluation of results is consistent and directly comparable with other studies. This relationship will become more evident in the following sections, where we describe the main methodology currently used by the IAM scientific community to make sure that there is consistency between their scenario studies.

2.1. Representative Concentration Pathways- RCP

In 2000, the Intergovernmental Panel on Climate Change (IPCC) released its “Special Report on Emission Scenarios”, or SRES (IPCC, 2000), in which possible alternative descriptions of the future were presented, based on a consistent set of

assumptions about the driving forces of socio-economic, technological and environmental development.

The SRES scenarios, as they were commonly known, presented global emissions projections of greenhouse gases, and during the following decade, served as a guideline for long-term scenarios, being used extensively in climate change research (VAN VUUREN *et al.*, 2012).

However, recently the scientific community identified the need to review or even replace these scenarios. MOSS *et al.* (2010) cite three main reasons for the development of new representative scenarios:

1. The SRES scenarios were developed with the premise of the absence of climate policies;
2. The improvement of climate models, which are based on more detailed data that originally provided (especially in terms of regional data);
3. The need for greater collaboration between the development of scenarios and their users, ensuring the consistency of their uses and their analysis.

Thus, new scenarios of long-term GHG emissions were developed by the scientific community. However, in order to ensure greater cooperation between the scientific community, the development process consisted of three stages: Preparatory; Parallel and Integration (VAN VUUREN *et al.*, 2012).

In the first stage, four emission scenarios were selected from the scientific literature. The emissions trajectories described by these four studies were defined as "Representative Concentration Pathways of" or RCP (Representative Concentration Pathways).

The second step involved the development of appropriate plotlines and socioeconomic scenarios that were consistent with the RCP. In this effort, the communities of IAM joined forces, more specifically the mitigation groups and the vulnerability, impacts and adaptation groups.

These groups differentiate themselves on the approach towards climate change. Mitigation are anthropogenic interventions that focus on trying to reduce or eliminate climate change and its impacts, which only comes at a cost to the economy, namely the mitigation cost.

Adaptation refers to limiting the vulnerabilities from climate change impacts, without dealing directly with the underlying cause. The focus is to be able to adapt current conditions of socioeconomic conditions and production processes to reduce the costs from absorbing the climate change impacts directly.

The basic relationship between mitigation, adaptation and impact are presented in Figure 2-1. In simple terms, actions toward adaptation or mitigation bring consequences to the other, whilst still affecting impacts from climate change. However, the true complication of this inter-relationship lies on two aspects.

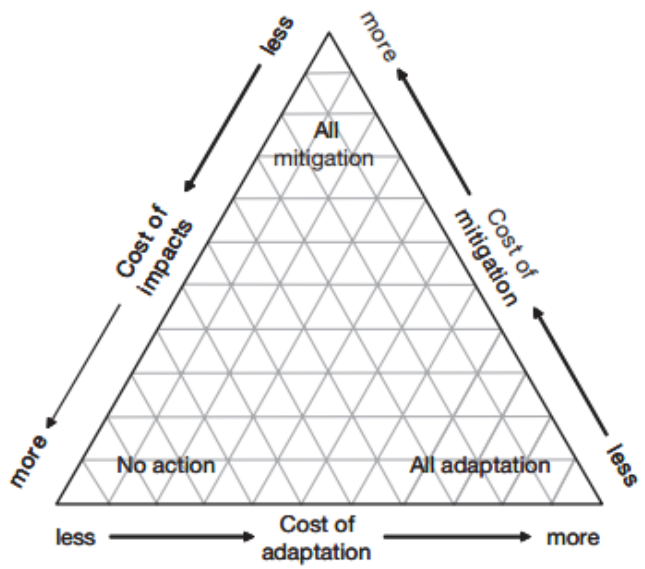


Figure 2-1 – Inter-relationship between adaptation, mitigation and impacts.
Source: IPCC (2007a)

Firstly, decisions on adaptation and mitigation are taken at different governance. Effective mitigation requires the participation of major global GHG emitters, whereas most adaptation takes place from local to national levels. Thus, mitigation is primarily driven by international agreements and ensuing national public policies, possibly complemented by unilateral and voluntary actions, whereas most adaptation involves private actions of affected entities, public arrangements of impacted communities, and national policies (IPCC, 2007a).

The second main issue is that it is not yet possible to answer the question as to whether or not investment in adaptation would buy time for mitigation. Understanding the specific economic trade-offs between the immediate localised benefits of adaptation and the longer-term global benefits of mitigation requires information on the actions'

costs and benefits over time. Integrated assessment models provide approximate estimates of relative costs and benefits at highly aggregated levels, but only a few models include feedbacks from impacts (IPCC, 2007a).

Thus, the developed scenarios could be used in the third stage, by the both research communities, promoting information on potential mitigation and adaptation simultaneously and consistently.

The RCP scenarios were selected to ensure a wide range of the main factor that determine the future climate: the radiative forcing. Even more, the RCP determine the trajectory for this factor and its indirect variables, such as concentration of greenhouse gases in the atmosphere.

Figure 2-2 presents the evolution of radioactive forcing according to the RCP. It can be easily identified that each scenario promotes the stabilization of radioactive forcing in a certain value. The four scenarios are:

- RCP8.5: setting with very high emissions stabilizing up to 8.5 W/m² (RIAHI *et al.*, 2007; RIAHI *et al.*, 2011);
- RCP 6.0: High stabilization scenario at 6.0 W/m² (MASUI *et al.*, 2011);
- RCP4.5: intermediate stabilization scenario, at 4.5 W/m² (CLARKE *et al.*, 2007; THOMSON *et al.*, 2011);
- RCP3.0 (or RCP2.6): high mitigation scenario, with stabilization around 2.6 W/m² (VAN VUUREN *et al.*, 2007; VAN VUUREN *et al.*, 2011).

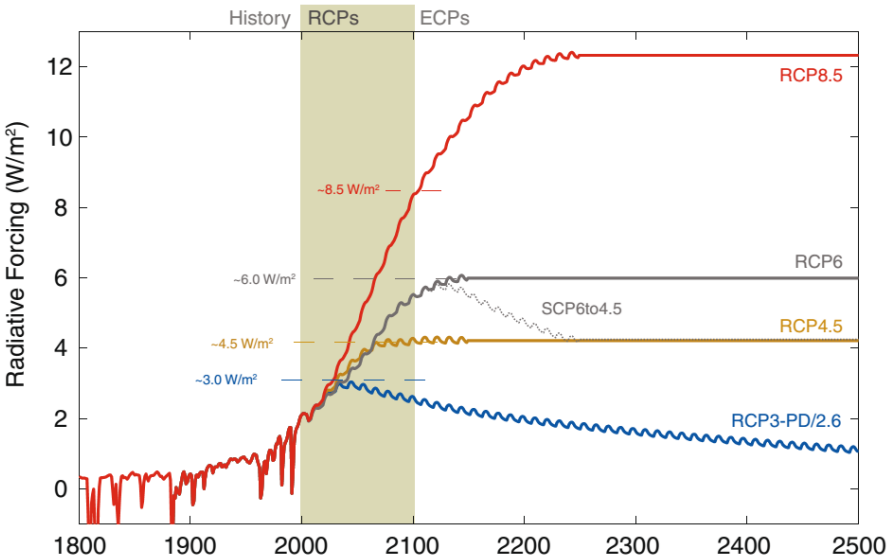


Figure 2-2 - Evolution of radiative forcing according to the RCP scenarios

Source: MEINSHAUSEN *et al.*, 2011

The RCPs were selected due to their unique characteristics in terms of emissions and concentrations of greenhouse gases. Figure 2-3 shows the difference of each RCP scenario in terms of its associated annual emissions of GHG. Thus, the scenarios were determined to unite the scientific efforts to study climate change, mitigation, impacts and vulnerability.

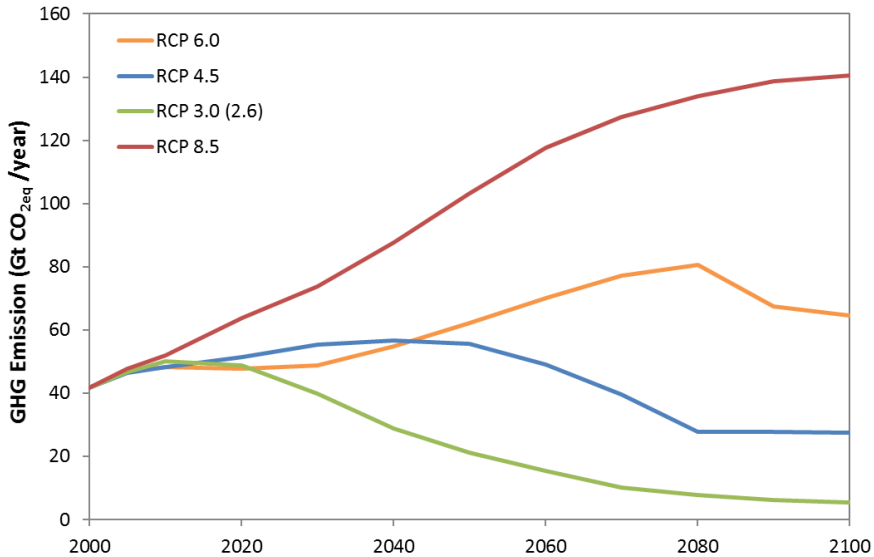


Figure 2-3 Projections of CO2 emissions by RCP scenarios

Source: own compilation using data from IIASA(2013a)

It is important to highlight that, despite representing a wide range of climate scenarios, the RCP scenarios were not selected on the merit of their socioeconomic assumptions. In addition, within the scientific literature they fit centrally in terms of demographic and economic changes (VAN VUUREN *et al.*, 2012).

In addition, there are numerous macro-economic projections that would be consistent with the RCP, i.e., whose socioeconomic projections would conform to the emissions profiles. For instance, VAN VURREN *et al.* (2012) show that several scenarios available in the literature meet the RCP, but they vary greatly in terms of population, GDP and energy consumption. Still, they also show that there is evidence to suggest that low emission scenarios would not be likely with a combination of high population evolution or high economic growth.

2.2.Shared Socioeconomic Pathways- SSPs

In this context, in November 2011 the scientific community, as established in Parallel step, the second phase of development of new scenarios, met in Boulder, USA, to develop the basic narratives of socioeconomic scenarios (O'NEIL, 2011). These scenarios were designed to be used jointly with the RCP, by the scientific community, to evaluate the issues of climate change, mitigation and adaptation.

The Boulder report, as it became known, determined a set of five projections of long term development, known as "Shared Socioeconomic Pathways", or SSP.

The scenarios were defined through different narratives for long-term global development and qualitative determination of the evolution of certain variables (such as population growth, economic, technological development), so that these scenarios could be built in more detail by different agents within the community (O'NEIL, 2011). Table 2-1 shows the key elements selected to characterize each scenario (O'NEIL, 2011; CHATEAU *et al.*, 2015; O'NEIL *et al.*, 2015).

Table 2-1- Characterization of the key parameters of the SSP scenarios

Elemento			*Grupos de países por faixa de renda (PIB per capita)*													
			SSP1			***SSP2***			***SSP3***			***SSP4***			***SSP5***	
			Low	***Medium***	***High***	***Low***	***Medium***	***High***	***Low***	***Medium***	***High***	***Low***	***Medium***	***High***	***Low***	***Medium***	***High***
Demographics	Population	**Growth**	Relatively Low			Medium	Medium	Medium	Relatively High			Misto			Relatively Low		
		Fertility	Low	Low	Medium	Medium	Medium	Medium	High	High	Medium	High	Low / Medium		Low	Low	High
		Mortality	Low	Low	Low	Medium	Medium	Medium	High	High	High	High	Medium	Medium	Low	Low	Low
		Migration	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low	Low	Low	Low	Low	High	High	High
	Urbanization	**Level**	-	-	-	-	-	-	-	-	-	High	High /Medium	Medium	High	High	High
		Type	Well managed			Historical pattern			Poorly managed			Mixed			Better management over time		
		Education	High	High	High	Medium	Medium	Medium	Low	Low	Low	Low	Medium	Medium	High	High	High
Socio-economic		**Growth**	Medium	Medium	Fast	Medium	Medium	Slow	Slow	Slow	Slow	Slow	Medium	Medium /Fast	High	High	High
		Struture	Service growths rapidly			-			-			-			Limited services / High consumption		
	Inequ ality	**Regional**	Convergent			-			-			High	High	High	Convergency towards High level		
		National	More equitable, less stratification			-			-			High	High	High	More equitable, less stratification		
		Inter. Trade	-			-			Strongly constrained			-			High, with regional specialization		
		Globalization	Connected markets			Medium			De-globalization			Connected elites			Strongly globalized		
		Consumption	Low growth			Intensive			Intensive			Different across levels			Materialism		
		Diet	Low meat diet			Average meat diet			-			-			Meat-rich Diet		
Policy and Instituitions		**Inter. Cooperation**	Effective			Moderate			Weak			Effective for elite and coorporations			Effective		
		Enviromental Policy	Improved for local and global			Moderate success			Low priority			Focus on local environment			Focus on local environment		
		Policy Orientation	Sustainable development			Sustainability			Security			Benefit of elites			Development, Free market		
		Instituitions	National and International			Uneven			Weak globaly			Segregation			Fostering competition		
Technologies		**Development**	Fast			Medium			Slow			Fast in high-tech economies			Fast		
		Transfer	Fast			Medium			Slow			Little transfer in poor countries			Fast		
		Energy (Change)	Directed away from fossil, towards efficiency and renewable			Energy balancing			Slow change, toward domectic sources			Fast Low-carbon (CCS)			Toward fossil fuels		
		Carbon Intensity	Low			Medium			High			Ambiguity			High		
		Energy Intensity	Low			Uneven			High			Ambiguity			High		
Enviroment and Natural Resources		**Fossil Constraints**	Shifts away form fossil			Use of unconventional resources			Use of unconventional resources			Anticipation of constraints			None		
		Enviroment	Improving			Degradation			Serious degradation			Managed in high income			Highly engineered		
		Land Use	Strong regulations			Medium regulations			Hardly any regulation			Tropical deforestation			Decline in deforestation		
		Agriculture	Best practices			Madium pace of change			Restricted trade			High productivity for large scale			Resource intensive		

As can be seen, the narratives explored a wide range of possible pathways, within the context of climate change. In addition to different socioeconomic trajectories, each SSP correlates with different challenges to mitigation and/or adaptation. Figure 2-4 shows how these scenarios behave according to these challenges.

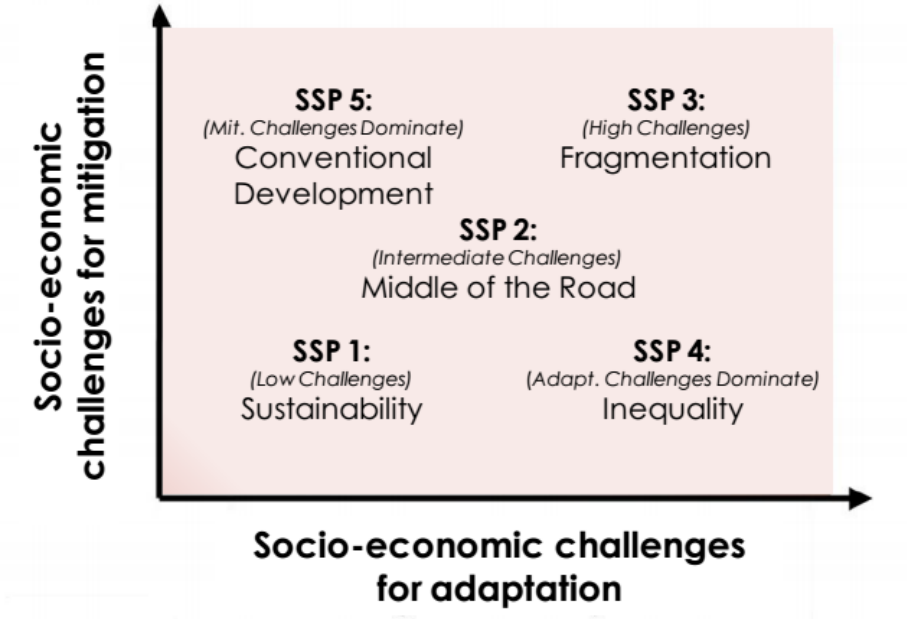


Figure 2-4 - Narratives of socioeconomic scenarios

Source: O'Neill et al 2011

Important to note that, as previously mentioned, there is a great combination of scenarios whose difficulties for mitigation and adaptation ensures a location within a single quadrant. According to O'NEIL *et al.* (2011), the SSP represent individual paths that are representative of the types of socioeconomic pathways that could occupy specific areas within the overall space.

The development of the next generation of long-term global socioeconomic scenarios must meet two competing challenges: support integrated research for mitigation of climate change and its impacts; and provide information for decision making and their agents. In this respect, the scenarios are intended for use by two different groups: on the one hand, researchers working on global or local level; on the other hand, the political sphere, whose decisions may differ from national or local level (O'NEIL, 2011; O'NEIL *et al.*, 2015).

Another major concern in the development of the new scenarios is to ease consistency between local or regional studies within the global standards determined by each SSP. The global scenarios act as a framework, outlining the boundary conditions,

but with some flexibility in a more localized level. Thus, they limit the scope of possible future conditions, without being prescriptive.

In recent years, scenarios have been developed to quantify the main variables, such as population and economic growth. Figure 2-5 shows how each scenario behaves for each of these variables, until 2100. Each projection is a quantitative representation of qualitative description given by Boulder report.

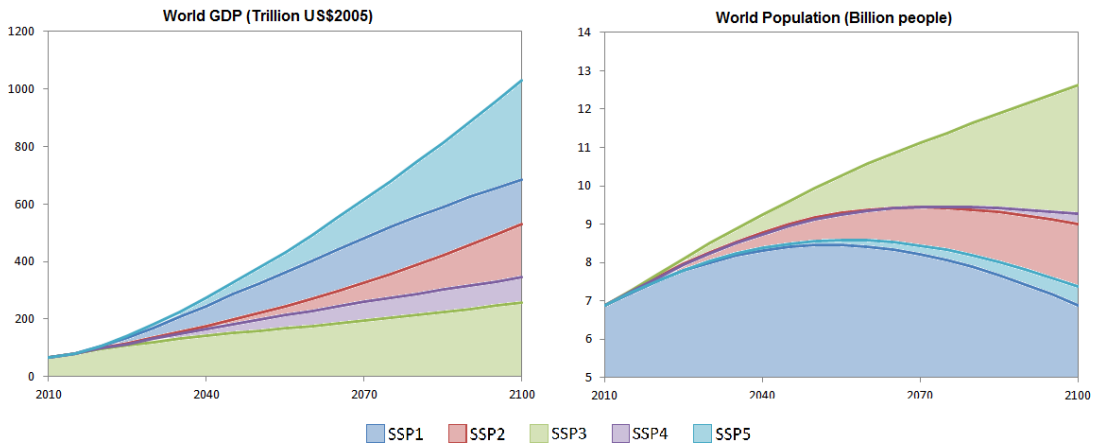


Figure 2-5 – GDP and population growth in the SSPs

Source: Source: own compilation using data from IIASA(2013b)

2.3.Integrated approach

As discussed, the motivation for the creation of new long-term global scenarios is to use the emission scenarios, RCPs, integrated with socio-economic scenarios, the SSP, in order to ensure methodological consistency within climate change research.

Figure 2-6 shows how the tools mentioned so far are related in the last step, called integration. At this stage, the scientific community is responsible for developing studies, global or local, through an integrated approach with the RCP, SSP and climate models to assess future options and decisions that favour mitigation or adaptation to global climate change.

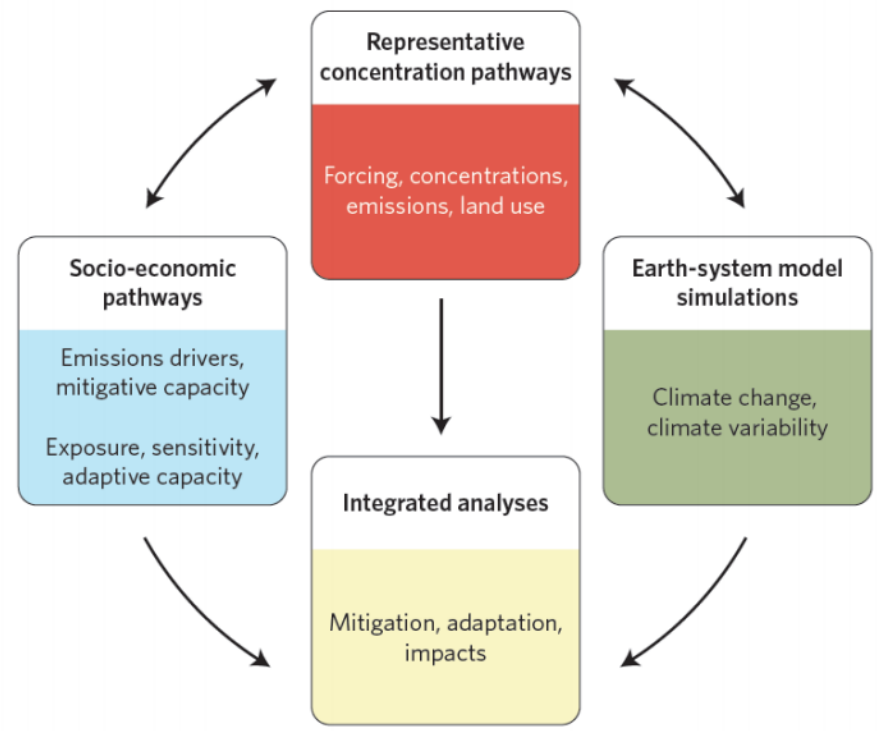


Figure 2-6 – Integration process

Source: O'NEIL, 2011

Under the integrated approach, it should be noted that there may be certain ideological inconsistencies between some assumptions of socio-economic scenarios (such as environmental policy, level of international cooperation and political orientation) and the trajectories described by the RCP.

For instance, a scenario that considers high international cooperation and policy orientation towards sustainability, great concern for the environment and improvement of air quality would not be completely consistent with a scenario that considers a high radioactive forcing stabilization. The same could be said towards combining a low radioactive forcing scenario, which would be impossible to be achieved without international cooperation and policies for addressing global GHG, with assumptions that favours local issues and large corporation interests.

Thus, compatibility matrixes between RCPs and SSPs are being proposed in the literature (O'NEIL, 2011; KRAM, 2012; VAN VUUREN *et al.*, 2012). Figure 2-7 is an example of such a matrix. In black, the incompatibilities between the narratives of the SSP and the necessary efforts to achieve the RCP are depicted.

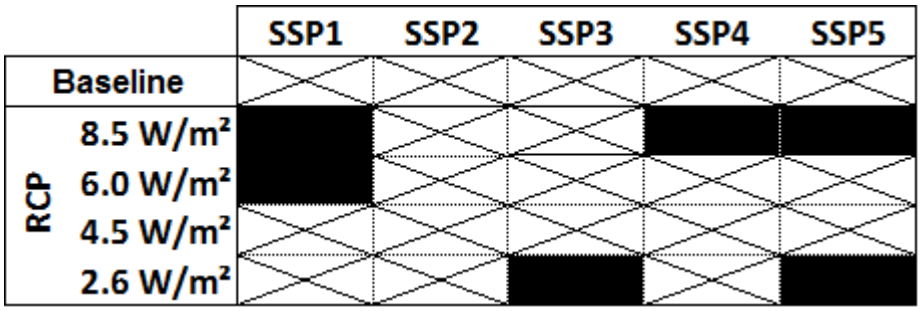


Figure 2-7 - Compatibility matrix between RCP and SSP

Fonte: adapted from KRAM, 2012

From matrices like this, it becomes possible to create a relationship between socioeconomic scenarios and their adherence to standardized global climate scenarios. This methodology is understood by the IAM community as the most appropriate to evaluate the possible effects of mitigation and/or adaptation to global climate change.

2.4. Global Integrated Assessment Models (IAMs)

This section provides an overview of IAMs and presents the most important ones in the literature. Integrated assessment models (IAM) have been developed to describe the interaction of human development and the natural environment. IAM draw on functional relationships between activities, such as provision of food, water and energy, economic activities and the associated impacts (IPCC, 2000; DICKINSON, 2007; IIASA, 2016; PBL, 2016).

The main advantage of this approach is that consistency is ensured throughout the economic sectors. Still, the impacts from an action by one agent, sector or region is linked and, therefore, affects other agents, sectors and regions. For instance, the balance between supply and demand for a commodity or even economic repercussions and chain effects of increased costs of energy input.

Traditionally, most IAMs focused on climate change and air pollution. More recently, these models have been expanded to assess an increasing number of impacts, such as air and water quality, water scarcity, depletion of non-renewable resources and overexploitation of renewable resources (PBL, 2016).

IAMs are designed to provide insight into how driving factors induce a range of impacts, taking into account some of the key feedback and feed-forward mechanisms. To achieve this effectively, IAMs need to be sufficiently detailed to address the problem, yet

simple enough to be applicable in assessments, including exploration of uncertainties, and without loss of transparency because of the complex relationships involved (PBL, 2016).

METCALF AND STOCK (2015) provide a brief discussion on the role of IAMs in climate policy, with interesting consideration from experts on the subject: John Weyant and Robert Pindyck. John Weyant argues that much of the uncertainty in the use of IAMs represents less the flaws of the models and more the fundamental uncertainty in scientific and economic knowledge of key model features and inputs. Weyant also stresses the importance of the research community improving how it reports and handles the wide range of uncertainty from IAM- based calculations.

On the other hand, Robert Pindyck also addresses the uncertainty in the IAMs but reaches a quite different conclusion: that the models are "of little or no value for evaluating alternative climate change policies" and that the models suggest "a level of knowledge and precision that is non-existent, and allows the modeller to obtain almost any desired result because key inputs can be chosen arbitrarily".

However, the main conclusion from METCALF AND STOCK (2015) agrees with Weyant. The authors argue that IAMs are important tools in developing climate policies, since there is no way that it can be done credibly without sophisticated computer models that incorporate climate and economic considerations. Furthermore, they argue that policy makers and economic agents need a clear understanding of climate targets and goals, and that is hard to see how that can happen without sophisticated integrated frameworks for computing marginal climate damages (METCALF AND STOCK, 2015).

The following IAM teams have participated in the development of the SSP scenarios: FEEM (*Fondazione Eni Enrico Mattei*), IIASA (International Institute for Applied System Analysis), PBL (*Planbureau voor de Leefomgeving*, or Netherlands Environmental Assessment Agency), NIES (*Kokuritsu-Kankyō Kenkyūsho*, or National Institute for Environmental Studies), PIK (*Potsdam Institut für Klimafolgenforschung*, or Institute for Climate Impact Research) and PNNL (Pacific Northwest National Laboratory). Each of which have contributed on a voluntary basis towards this process (IIASA, 2015).

Key criterion in order to participate in this process included the ability to provide detailed reporting on emission as well as on land-use variable (IIASA, 2015). Other research groups fall into this restrictive description. Table 2-2 shows a summary of the main groups of integrated modelling in the world, highlighting the model, institute and country of origin.

Table 2-2 - Characterisation of the main global models

Model	Institute	Country	Classification	Algorithm
AIM/CGE	NIES	Japan	General Eq	Recursive Dynamic
GCAM	PNNL	USA	General Eq	Recursive Dynamic
IMAGE-TIMER	PBL	Netherlands	General Eq	Recursive Dynamic
MESSAGE-Globiom	IIASA	Austria	General Eq	Intertemporal Optimization
REMIND-MagPIE	PIK	Germany	General Eq	Intertemporal Optimization
TIAM-TIMES	ETSAP	France	Partial Eq.	Intertemporal Optimization
MERGE	EPRI	USA	General Eq	Intertemporal Optimization
WITCH	FEEM	Italy	General Eq	Intertemporal Optimization
EPPA	MIT	USA	General Eq	Recursive Dynamic

Source: IIASA, 2015

All the following model descriptions are taken from IIASA (2015):

–The *Asia-Pacific Integrated Assessment/Computable General Equilibrium* (AIM/CGE) is a recursive type dynamic general equilibrium model that covers all regions of the world. The AIM/CGE model includes 17 regions and 42 industrial classifications. Likewise, other CGE models, AIM/CGE deals with whole economic production and consumption behaviours with particular emphasis on the representation of energy in order to assess energy related CO2 emissions appropriately.

–The Global Change Assessment Model (GCAM) is a global integrated assessment model with particular emphasis on the representation of human earth systems including interactions between the global economic, energy, agricultural, land use and technology systems. The GCAM physical atmosphere and climate are represented by Hector, an open source coupled carbon cycle-climate model. The GCAM is global in scope and disaggregated into 14 geographical regions, 32 energy and economic regions and 283 agriculture and land use regions. GCAM is a dynamic-recursive market equilibrium model. GCAM is open-source and can be downloaded.

–The IMAGE/TIMER Integrated Assessment Modelling Framework consists of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change (see Figure 2-8). The global energy model that forms part of this framework, TIMER, describes the demand and production of primary and secondary energy and the related emissions of GHGs and regional air pollutants. The model has 26 regions, but the land distribution of natural vegetation and crops is determined on the basis of climate conditions and soil characteristics on a spatial resolution of 0.5 x 0.5 degree.

–Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) is an 11 region energy engineering model based on a linear programming (LP) optimization approach which is used for medium- to long-term energy system planning and policy analysis. MESSAGE is linked to a macro-economic model - MACRO. In MACRO, capital stock, available labour, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function (See Figure 2-9). The Global Biosphere Management Model (GLOBIOM) is a partial-equilibrium model represents various land-use based activities, including agriculture, forestry and bioenergy sectors. The model is built following a bottom-up setting based on detailed grid-cell information, providing the biophysical and technical cost information. Its spatial equilibrium modelling approach represents bilateral trade based on cost competitiveness.

–The Regionalized Model of Investment and Technological Development (REMIND) is a global multi-regional integrated assessment model that couples a top-down macroeconomic growth model with a detailed bottom-up energy system model and a simple climate model. By embedding technological change in the energy sector into a representation of the macroeconomic environment, REMIND combines the major strengths of bottom-up and top-down models. The Model of Agricultural Production and its Impacts on the Environment (MAgPIE) is a global multi regional partial equilibrium model of the agricultural sector. MAgPIE links demand for 10 economic world regions with spatially explicit biophysical inputs such as land, agricultural yields and water availability.

– The World Induced Technical Change Hybrid model (WITCH) is a hybrid top-down economic model with a representation of the energy sector of medium complexity. Two distinguishing features of the WITCH model are the game theoretic set-up, which is particularly useful for analysing fragmented international policy settings, and the representation of endogenous technological change. World countries are grouped into thirteen regions. Innovation spills across regions in the form of knowledge, with important repercussions on the optimal R&D investments that major economic actors decide to undertake. WITCH is an inter-temporal optimization model in which perfect foresight prevails over a time horizon covering the whole century.

As it can be seen, all major global IAMs were developed in OECD countries. Additionally, they are concentrated on only a few countries. This leads to the conclusion that the OECD countries and, arguably the richest countries in the world, hold much of the contribution of the international scientific community of integrated assessment modelling on long-term climate change scenarios.

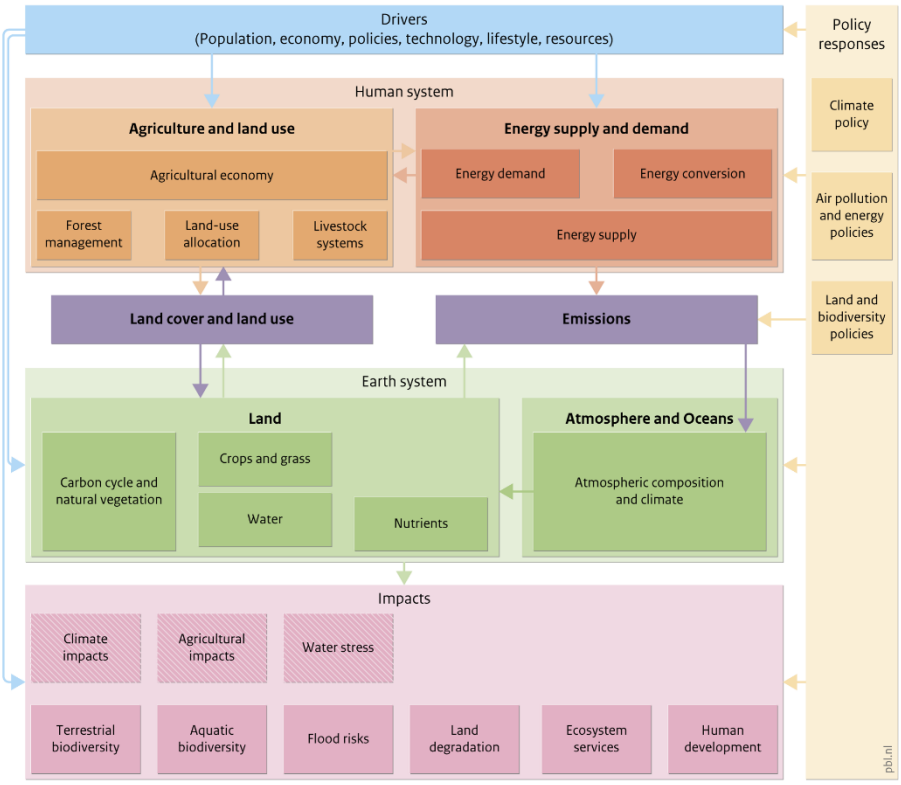


Figure 2-8 – IMAGE-TIMER framework

Source: PBL, 2016

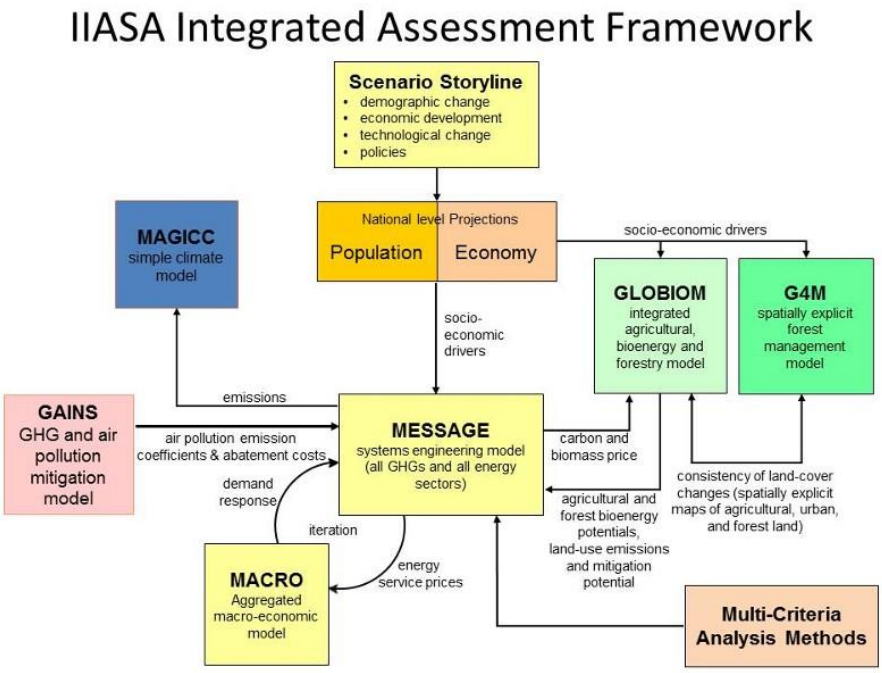


Figure 2-9 – IIASA IAM framework

Source: IIASA, 2016

Thus, in spite of the Brazilian role in negotiations associated with UN conferences, these groups have a strong influence by technically supporting decisions on individual national contributions in climate stabilization plans, such as the Paris Agreement provides. In this context, these groups indubitably have a strong influence on fostering decisions on global targets and, consequently, on individual national contributions related to climate stabilization plans.

This fact demonstrates the sensitive position of countries like Brazil, since the analysis of the Brazilian contribution to climate scenarios is being evaluated and determined by countries with different objectives, hypothesis and priorities about the development of their nation, economy and people.

For this reason, the development of a mathematical tool that allows Brazil to locate itself in a more robust and adequate position in international negotiations, while becoming a nation that has a global model, is timely and desired. This objective appears as an important strategic decision that aligns with the proposal of this thesis. A global model developed in Brazil does not only provide greater capacity to better understand the country's role in international climate negotiations, but it is also an unprecedented tool within the southern and developing countries.

3. Methodology

As discussed in previous sections, the aim of this study is to investigate the role Brazil can play in the long term global climate stabilization context within an integrated energy modelling approach. To make this assessment judiciously, it becomes necessary to prepare a set of mathematical tools and methodological procedures, which are discussed in this chapter.

Currently, the scientific community is developing studies, global or local, through an integrated approach with the RCPs, SSPs and climate models to assess future options and decisions that favour mitigation or adaptation to global climate change.

From the perspective of the integrated approach, this study aims to assess the socio-economic and energy implications for Brazil. It is worth noting that this study will focus on the assessment of the effects of mitigation to climate change. Effects of adaptation are out of the scope of this study and can comprehend in a series of future studies derived from this thesis.

3.1.MESSAGE

In pursuing the purpose of this research, it is necessary to elaborate robust mathematical models. The main computational tool proposed to carry out this analysis is the MESSAGE (Model for Energy Supply Strategy Alternatives and Their General Environmental Impacts), an optimization software in linear programming for energy systems developed by IIASA (International Institute for Applied System Analysis) (IAEA, 2007; GRITSEVSKYI AND NAKICENOV, 2000).

This is one of the tools used by the research community of climate change, including one of the working groups that determined the RCP and SSP. In simple terms, the model is designed to meet the demand for energy services (exogenous to the model), given the competition between technologies and energy sources, with the objective of minimizing the total cost of the system (BORBA, 2012).

In turn, the MESSAGE-Brazil model is a version of the optimization software for energy systems, which has been adapted for many years by CENERGIA (PPE/COPPE) researchers for the Brazilian energy system. BORBA (2012) reports that there are in the literature several studies using the MESSAGE to analyse energy mix scenarios for

medium and long-term public policies in several countries (IAEA, 2006; KLAASSEN AND RIAHI, 2007; LIU *et al.*, 2009; SARADHI *et al.*, 2009; HAINOUN *et al.*, 2010; MOHAPATRA AND MOHANAKRISHNAN, 2010).

The first version of MESSAGE-Brazil was made for a study with the International Atomic Energy Agency (IAEA, 2006). Since then, it has been held constant effort to develop and update the MESSAGE-Brazil. Some application examples of MESSAGE - Brazil can be found in NOGUEIRA (2016), ROCHEDO *et al.* (2016), KOBERLE *et al.* (2015), LUCENA *et al.* (2015), MARTÍNEZ *et al.* (2015), NOGUEIRA *et al.* (2014) and BORBA *et al.* (2012).

The platform is designed to develop and evaluate alternative strategies for energy supply, in line with restrictions such as limits for investments, availability and fuel prices, environmental regulations and market penetration rates for new technologies, among others. Environmental aspects can be evaluated counting up and, if necessary, limiting emissions of pollutants by various technologies at various levels of the energy chain. This helps to assess the impact of environmental regulations on the development of the energy system.

In order to make this possible, the analyst must construct the energy flows that describe the energy system from the level of energy resources to the end or useful consumption, through all levels (primary, secondary and auxiliary) needed along the chain (HAINOUN *et al.*, 2010).

Among these energy levels, conversion technologies must be specified with the appropriate parameters and constraints such as installed capacity, potential availability, capacity factors and efficiencies, investment costs, variable and fixed life of the production units and expansion restrictions. In addition, the model allows also to include environmental constraints, such as for emission of GHG, which is of fundamental importance to carry out this research.

The total cost of the system includes the investment costs, operating costs and additional costs, such as "penalties" for certain alternatives, such as environmental and social costs. The total value is calculated by discounting all the costs that occur at later points per year basis for the case study, and the sum of the discounted total costs is used to find the optimal solution. This approach allows a realistic assessment of the long-term role of energy supply options in competitive conditions (HAINOUN *et al.*, 2010).

All restrictions on, for instance, the availability of resources, availability of infrastructure for transmission and distribution of energy and possible environmental constraints need to be met within the scenario (KEPPO AND STRUBEGGER, 2010).

The costs and performance characteristics (efficiencies, capacity factors, environmental indicators, etc.) of technological alternatives are amongst the most important input data for the model. These values can change through the time scale of the scenario, and is arguably a very sensitive input data on the model. In all, all these data are used to form energy vector prices and promote competition between alternative technologies for meeting the demand.

The energy demands can be divided regionally and in certain cases, as for electricity, it is possible to represent the system load curve. Each primary energy source can be divided into an optional number of classes, taking into account the extraction costs, quality of the sources and location of deposits. This stratification allows to represent in the model the non-linear relationships between extraction costs and the amount of available resources. Then these primary sources are transformed, directly or indirectly, into secondary and final sources and, finally, into energy service to meet the demand.

An interesting aspect of models such as MESSAGE, emphasized by NOGUEIRA (2015) and BORBA (2012), is that the optimized solution provides the minimum overall cost of the energy system, which does not necessarily reflect the optimum solution for each individual sector, such as Industry, within the energy system. It is such a feature, after all, which makes MESSAGE an integrated analysis model, able to identify the indirect effects of the restrictions set forth in one sector over others.

It is worth mentioning, however, that the adoption of an optimization model under a minimum overall cost perspective tends to provide results that reflect the optimal conformation of an energy system in a perfect competition, which does not occur in reality. For instance, it considers perfect information, no entry and exit barriers, no transaction costs and homogeneous opportunity cost of capital.

Thus, it is extremely important to create and calibrate constraints into the model. These constrains are imposed into, for instance, production and capacity expansion and make the model resemble the market imperfections. Thus, adding to the results more reality and reliability, especially in the short term.

In recent years, the version of the model developed for the Brazilian energy system has been substantially updated and applied to assess issues relevant to the national reality (LUCENA *et al.*, 2010; BORBA, 2012; NOGUEIRA *et al.*, 2013; LUCENA *et al.*, 2015).

More recently, the model has been completely reconfigured to ensure a better detailing of both the regional breakdown, as well as endogenous energy efficiency and GHG mitigation options in the end-use sectors. This version was called MSB8000 precisely the amount of technological options that make up the national energy model (ROCHEDO *et al.*, 2016).

3.2. Global Model

Despite all the experience in the development and use of a detailed energy model for Brazil, the Brazilian national model in its current form should be enhanced in relation to interactions with the rest of the world.

On the other hand, the overall level of detailing within the global model does not need to keep up the degree of sophistication of the latest version of MESSAGE-Brazil (ROCHEDO *et al.*., 2016). Indeed, the main purpose of this study is to have a proper representation of Brazil in a global optimization model of energy systems.

Therefore, the most consistent methodology derives from the midpoint, through the combination of the detailed model for Brazil, available at PPE/COPPE, and a global model to be developed in this thesis, highlighting Brazil as a separate region in the world, apart from other key regions, as it happens to be the case in several global models. Moreover, it is a clear scientific opportunity for Brazil to expand its knowledge of international energy systems, the evolution of socioeconomic narratives and their possible interactions with the country.

After analysing the regional breakdown of most of the global energy models and general equilibrium models, the range of regions seems to be between 8 and 26 regions, as the divisions agreed by the various groups of energy and economic modelling (IIASA, 2015). In this study, an 18 regions model is proposed, following the representation within Figure 3-1.

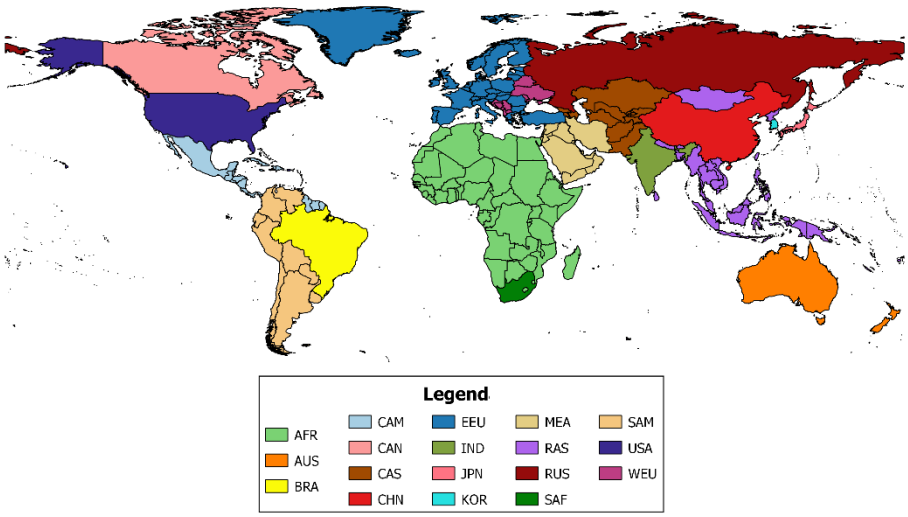


Figure 3-1 – Regional breakdown of global model

In addition, the motivation behind this structure, besides ensuring consistency with the SSP database (IIASA, 2013b), is to emphasize developing countries or economic groups with possible energy and environmental importance in the long run. In this way, they are separated according to their relevance:

- BRICS (Brazil, India, Russia, South Africa and China): economic and energy importance in the future;
- South Korea: future economic importance and core region of future technological innovation;
- USA, European Union and Japan: Current economic importance and energy.

The remaining countries were grouped according to the SSP database (IIASA, 2013b), with the exception of Pakistan, Indonesia, the countries of Oceania and the countries of Asian plains. Finally, the division involved categorizing 255 countries into the final 18 regions, which are shown in Table 3-1.

Is worth noting that this structure was also a result of the need to address the issue of heterogeneity and access to the necessary information, such as the macroeconomic data, detailed data on the energy sector and consumption profile of these regions.

Table 3-1 – Description of the 18 regions

Tag	Description
AFR	Africa[1]
AUS	Australia and New Zealand
BRA	Brazil
CAM	Central America
CAN	Canada
CAS	Caspian Region
CHN	China
EEU	East European (EU)
IND	India
JPN	Japan
KOR	South Korea
MEA	Middle East
RAS	Rest of Asia and Oceania
RUS	Russia
SAF	South Africa
SAM	South America[2]
USA	United States
WEU	West Europe

Notes: 1- Excluding South Africa; 2- Excluding Brazil.

3.3.Structure of the Model

In this section, the structure of the model within the MESSAGE framework will be addressed. The first noticeable feature of the model is that, unlike the previous description of the regions, the model itself is technically composed of 19 regions: all 18 regions, already detailed in the previous section, and a global region. This external region, contains and combines all 18 regions, as shown in Figure 3-2. Its main function is to account for international trade and related GHG emissions.

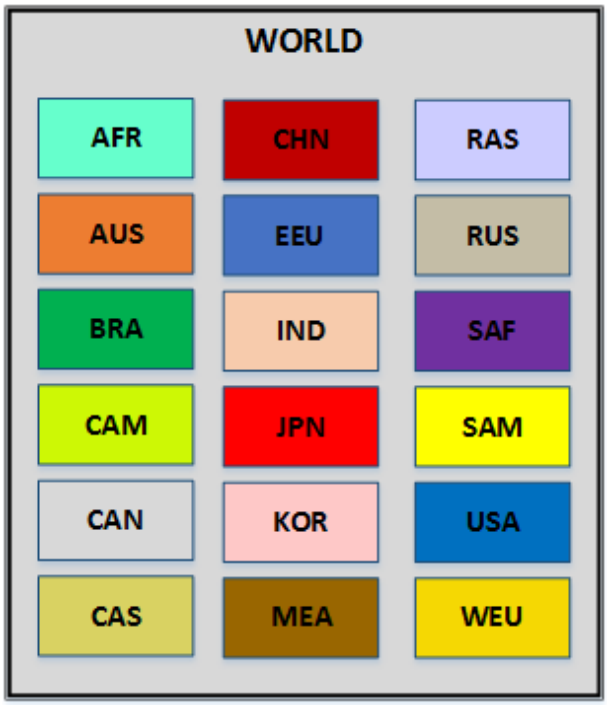


Figure 3-2 – 19 regions within MESSAGE

As for each of the 18 regions, Figure 3-3 shows a simplified representation of the energy chain. Every single region has its own unique resources, which will be further detailed in the next chapter. Resources include not only deposits of non-renewable energy sources or potential of renewable sources, but also land and reservoir capacity for carbon storage[3].

From the resources, the energy systems produce all primary energy that is transformed into secondary and, even further, final energy. All three of these energy levels can be imported to other regions or imported from other regions, if the constrains and costs associated with them deems it necessary. For instance, this is the case of regions with either no or low oil resources or even resources with high cost of production.

[3] Will be further detailed in the next chapter.

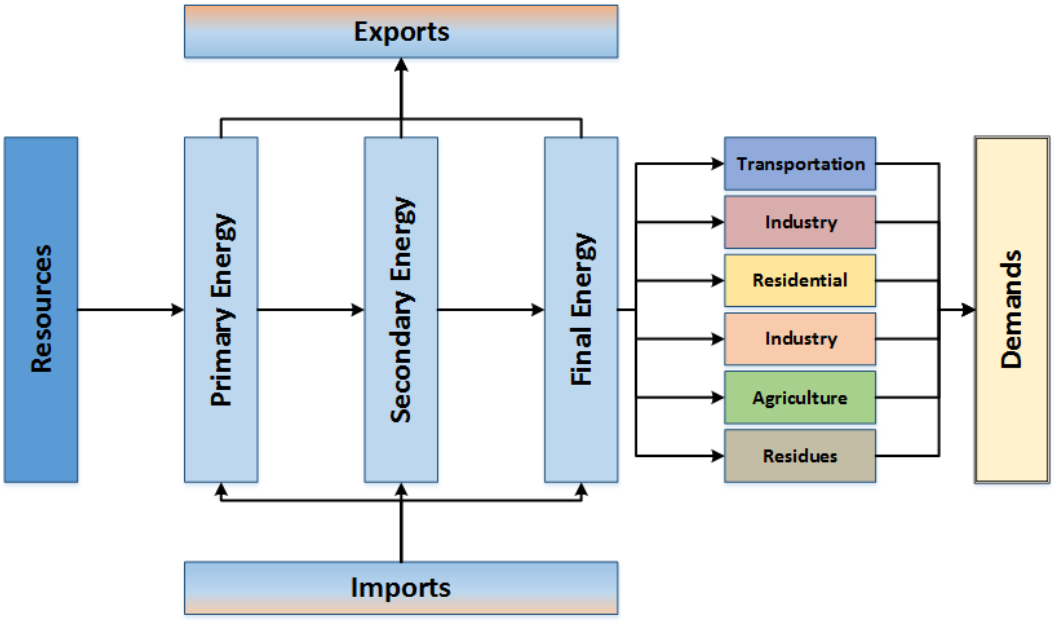


Figure 3-3 – Energy structure for every region of the model

Once all the necessary energy vectors are either produced, exported or imported, they are transferred into the final consumer sectors. In each sector, all final energy sources are transformed into the necessary energy services. The energy services are the objective of using energy. For instance, the Industry sector can use all sort of energy forms to generate heat, steam, driving force, lightning, cooling, etc. All energy services for each sector are the exogenous demand that the model needs to meet at minimum cost.

Besides the energy systems, another relevant aspect of IAMs is the land use, land use change, forestry and agriculture sector. Not only does this sector is strongly linked to climate change by itself, but there is also a strong connection between the land sector and the energy sector.

Currently, this is specially true for Brazil, where historically land use emissions are the most relevant aspect of total GHG emissions (MCTI, 2013). Moreover, sugarcane is the second most important source of primary energy in the country, because of ethanol production and cogeneration from bagasse.

Despite the Brazilian current condition, within long term scenarios bioenergy are extremely important for meeting climate targets (CHUM *et al.*, 2011; CLARKE *et al.*, 2014; BERTRAM *et al.*, 2015; DAIOGLOU, 2016). However, the mitigation potential that arrive from bioenergy use have a complex relationship, because it affects the carbon balance of both the land and the energy systems (DAIOGLOU, 2016).

The approach used for integrating the land system into the energy system is represented in Figure 3-4. In this simple description, different types of land covers can be modified between one another. In addition, certain type of land covers can be used for agricultural production, in order to meet the demand for food. Furthermore, just as for energy sources, agricultural products can be imported or exported from a single region to another.

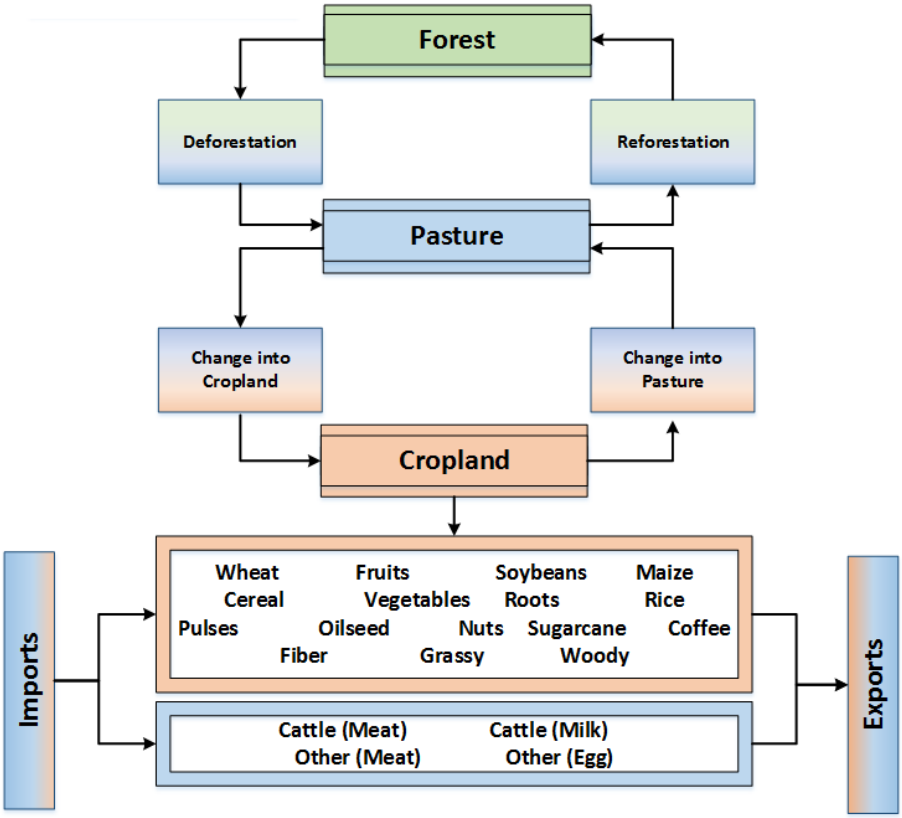


Figure 3-4 – Land Use structure for every region

In order to address the trade of energy and agriculture products between regions, a broader region is used within MESSAGE framework. This region is responsible for creating the trade flows between all 18 regions, while accounting for emissions of GHG resulting from such trades.

Figure 3-5 presents the simple relationship between each region during international trade of products. In order to simply this behaviour, the bunker consumption is attributed to the exporting region only.

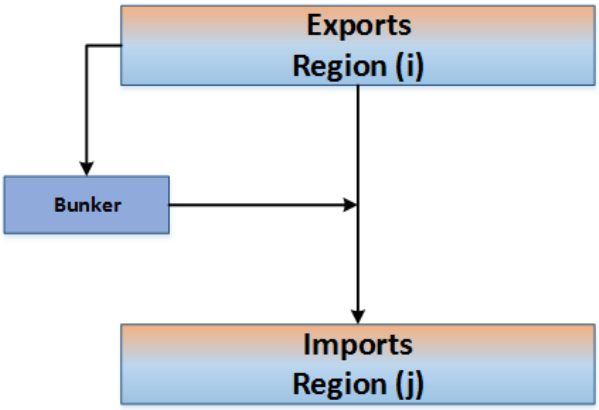


Figure 3-5 – Structure for Imports and Imports within the World Region

3.4. Input Data

The initial stage of the construction of the model is composed mainly of creating all necessary information for a database. This includes economy, social and energy data for all countries of the world. Several international databases were used by this study, mainly the World Bank (WB, 2013), reports of energy statistics of OECD and non-OECD by IEA (IEA, 2011a, IEA, 2011b), geological data of energy resources (MASTERS *et al.*, 1994; ROGNER, 1997; USGS, 2000; USGS, 2012; WEC, 2013), data for land use and agriculture production from FAO (FAO, 2016) and even microeconomic and macroeconomic data from several countries (WIOD, 2014).

This survey allows for the systematic description of the global energy system, and more importantly to adjust the database and the base year. The year 2010 was selected as a base year for the model.

Additional information from this survey includes the description of the regional resources of oil and gas, both conventional and unconventional, coal and uranium. From the quantification of these categories, a global supply curve for each non-renewable resource was developed and compared with that of other studies in the literature (for example MCGLADE AND EKINS (2014) and IEA (2014)).

Beyond that, natural resources such as wind, hydro and solar potentials were also estimated using published data for each region, creating the envelope for capacity expansion of renewables in the global energy sector.

In addition to data on the production of resources, information on transformation sector were also compiled. They include installed capacity and technical description of

power plants, CHP plants and the oil refining sector. For instance, the latter was addressed by estimating the capacities of all process units (OGJ, 2011) and then using them in the refining simulation tool called CAESAR (Carbon and Energy Strategy Analysis for Refineries), described in GUEDES (2015). With this tool, the petroleum products production profile and the oil refineries' utilities consumption for each region were estimated, albeit in simplified form. These results will be described in chapter 5.

Another novelty assessment of this study is the detailing and quantification of a reservoir supply curve for the geological storage of carbon dioxide. Through literature data and estimates, it was possible to conjecture a curve that combines the storage potential with the storage costs detailed by reservoir type (such as oil fields, gas and aquifers) and transport distance (ranges below 100, 500, 1,000 and 2,000 km from the source). These results will be described in chapter 4.

In addition to the data presented so far, the survey of several other global energy system data becomes necessary in developing the new global MESSAGE model. In addition to all the data on energy resources and supply, whether electric or fuel, it was also necessary to explore the behaviour of energy consumption in the demanding sectors. Thus, we needed to estimate the demand curves of energy services for the sectors of the economy of each region, as shown in Figure 3-3.

It is worth noting that the demand for energy services of each of the sectors listed above will directly result from the narratives of socioeconomic scenarios. This fact underscores the importance of quantitative description of SSP scenarios.

Moreover, the survey and analysis of an extremely high amount of data of different natures (from production and reserves of oil, to technical coefficients and consumption profiles) is a highly complex stage, given the heterogeneity of official information available in different countries.

However, this step is vital for the proper development of the database, which will be inserted into the global energy model. It is precisely this data that allows for a consistent, representative and adequate model, which is able to achieve the desired analysis in this work. This emphasizes the importance of this study, as the first global model of energy optimization developed entirely in Brazil, as will be shown along this work

4. Energy Resources

In this chapter, the data gathered, processed and estimated related to energy resources are detailed. They include not only deployable resources, such as coal, oil and gas, but also renewable resources, such as wind, hydro and solar potentials. Additionally, a single non-energy resource is also discussed, due to its close relationship with the energy systems: carbon dioxide geological storage capacity.

It is worth noting that finding detailed homogenous information about resources for every single country or region is not common, and, in fact, it proved to be a relevant issue in the making of this survey. That is why, whenever possible, a single homogenous source of information was preferred, instead of several dispersed sources of information. Nonetheless, the latter had to be used very often as well.

4.1. Oil and associated gas resources

The first energy resource to be addressed is precisely the most important primary energy in the world, oil. With about 31% of the total primary energy demand of the world (IEA, 2015), just considering crude oil, it comprises the most important and flexible primary energy source of the world.

While there are several studies assessing the distribution and evolution of oil reserves available in the scientific and technical literature, only few studies deal with estimates for total oil resource distribution throughout the world, particularly when including unconventional resources (ROGNER, 1997; USGS, 2000; USGS, 2012; MCGLADE, 2013; WEC, 2013; IEA, 2014; MCGLADE AND EKINS, 2015). In addition, some of the most comprehensive studies are outdated or specific to a single country or region.

One of the best-known assessments for the world's hydrocarbon resources is ROGNER (1997). Indeed, that study was one of the guidelines and inspirations towards the new survey developed in this study. ROGNER (1997) has established an assessment for coal, oil and natural gas resources, including unconventional resources, dividing the world in 11 regions. For oil, the study estimated about 2,638 Gt of oil, where about 23% and 22% were estimated to be in North America and Middle East, respectively.

Despite being one of the most comprehensive assessments for oil resources, some of the data used during that study have become outdated, especially those related to undiscovered and unconventional resources. Nonetheless, that study still provides great insights on the subject and several useful detailed information on resource estimations and technical parameters relating to resource assessments.

Among the most recent studies on the subject, the assessment in MCGLADE (2013) deserves special attention. That study provides a full description of the uncertainty in the resource potential of all individual categories of oil and gas, including estimating the uncertainty in resource availability at different costs of production, and examining the resource potential of categories that have been previously overlooked (MCGLADE, 2013). The findings of that study were summarized in MCGLADE AND EKINS (2015).

The detailed economic approach of that study was responsible for creating the most comprehensive supply curve for oil resources available in the literature. Specific costs and production parameters, such as depletion curves, were estimated for every type of resources and for every region of the model.

In addition, the study adopted a stochastic approach, instead of the standard deterministic approach, to create a probabilistic supply cost curves for oil production. Figure 4-1 presents this curve, where the red line is the medium value, the green area is related to a 50% certainty and the blue area related to a 5% certainty.

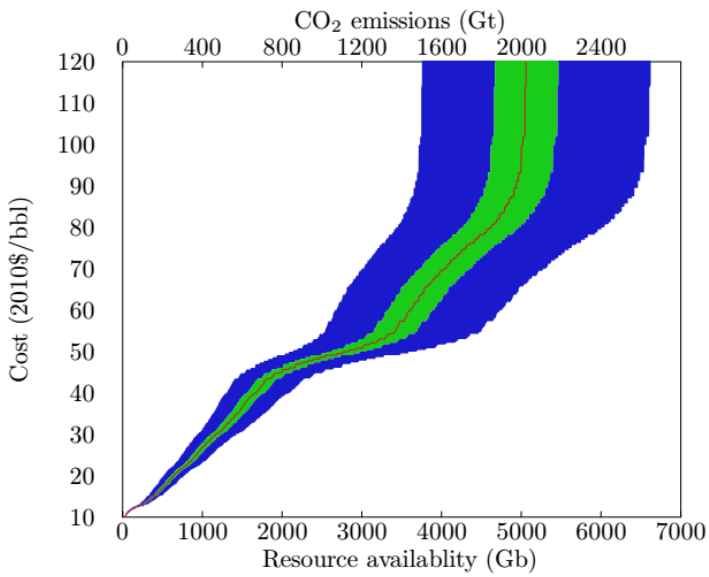


Figure 4-1 – Oil resource availability

Source: MCGLADE. 2013

All the studies mentioned so far contributed to the survey conducted in this work. However, it should also be highlighted the importance of the "World Petroleum Assessment", with the USGS (2000), USGS (2012) or the individual region updates. The United States Geological Survey (USGS) provides an assessment of the quantity, quality, and geologic distribution of world oil and gas resources. In the USGS website all the data on detailed assessments for oil, natural gas and natural gas liquids (NGL) for almost every basin in the world can be downloaded.

Crude oil development and production can include up to three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. During primary recovery, the natural pressure of the reservoir or gravity drive oil into the wellbore combined with artificial lift techniques (such as pumps), which bring the oil to the surface. Secondary recovery techniques extend a field's productive life generally by injecting water or gas to displace oil and drive it to a production wellbore.

Finally, Enhance Oil Recovery (EOR) is a set of techniques for increasing the amount of crude oil that can be extracted from an oil field. This extends the oil field's life, but production costs increase. There are mainly three technologies for EOR[4], one of which is injecting CO_2 into the reservoir. For more information on EOR technologies, see IEA (2013).

Additional production from EOR was estimated according to regional coefficients derived from ROGNER (1997). The ratio between the resources available through EOR and the sum of discovered and undiscovered conventional resources was estimated for each of the 11 regions considered in that study. As explained before, the remaining seven regions of this thesis had their estimates based on assigning the value of the aggregated region or a neighbouring region. Table 4-1 presents an estimated compatibility between the regions used in this study and ROGNER (1997).

[4] There are mainly three Technologies of EOR: Thermal recovery, which usually involves adding steam to lower the viscosity and improve flow; Gas injection, which uses a gas (CO_2, N_2, methane) to push or dissolve the remaining oil improving flow; Chemical injection, which involves adding polymers or surfactants to lower surface tension of oil droplets.

Table 4-1 – Compatibility of regions between ROGNER (1997) and this study

Regions in ROGNER, 1997	Description of Regions	Regions included (this study)
NAM	North America	CAN USA
LAM	Latin America	BRA CAM SAM
WEU	Western Europe	WEU
EEU	Eastern Europe	EEU
FSU	Former Soviet Union	WEU RUS
MEA	Middle East and North Africa	MEA AFR
AFR	Sub-saharan Africa	AFR SAF
CPA	Centrally Planned Asia and China	CAS CHN RAS
SAS	South Asia	IND RAS
PAS	Pacific Asia	RAS
PAO	Pacific OECD	AUS JPN KOR

Hence, the ratio between the resources available through EOR and the sum of discovered and undiscovered conventional resources were applied for onshore and offshore resources, separately. Clearly, in the lack of better information, this is a heroic assumption: EOR techniques are able to provide the same increase in production wherever the resource is available. By doing this simplification, resources available through EOR methods were disaggregated into onshore and offshore.

The result shows an increase in production between 13% and 27%, which agrees with the range suggested in MCGLADE (2013), of 5% to 25%. Besides, MCGLADE (2013) also argues that CO_2 EOR could contribute with an additional reserve growth of 469 Gbbl, globally. The estimated value in this thesis was of 430 Gbbl.

As for estimated production costs, the main data source was MCGLADE (2013), which in turn adapted data from IEA (2011). MCGLADE (2013) and IEA (2009, 2011, 2013b) provide little information for regional adjustment in cost. Exceptions include conventional crude oil production in Middle East (MEA), heavy oil production in Venezuela (SAM), and very few projects around the world. Therefore, whenever

possible, data presented in Table 4-2 were used. Minor adjustments were made, within the cost range, in order to adjust into the oil categories of this study.

Table 4-2 – Cost data for crude oil production

Oil category	Bound	Cost relationship	Cost (2010$/bbl)	
			Min	Max
Reserves	Lower	Cost database (based on min IEA range)	10	26
	Upper	Cost database (based on max IEA range – finding cost)	20	41
Reserve growth	Lower	Lower reserves cost + $10/bbl	20	36
	Upper	Upper reserves cost + $40/bbl	60	81
Undiscovered	Lower	Lower reserves cost + regional finding cost	11	33
	Upper	Upper reserves cost + regional finding cost + $40/bbl	62	89
DW reserves	Lower	Cost database (based on min IEA range)	40	50
	Upper	Cost database (based on max IEA range – finding cost)	44	58
DW reserve growth	Lower	Lower DW reserves cost + $10/bbl	50	60
	Upper	Upper DW reserves cost + $40/bbl	89	98
DW undiscovered	Lower	Lower DW reserves cost + US offshore finding cost	47	57
	Upper	Upper DW reserves cost + US offshore finding cost + $40/bbl	96	105
Arctic oil	Lower	Min IEA range	40	40
	Upper	Max IEA range	100	100
Light tight oil	Lower	Discounted cash flow analysis	30	40
	Upper	Discounted cash flow analysis	60	80

Source: MCGLADE (2013)

Notes: DW means Deepwater.

Therefore, by using detailed resource assessments in USGS (2000), USGS (2007), WEC (2010), USGS (2012), WEC (2013) and MCGLADE (2013), detailed technical parameters (such as Enhanced Oil Recovery, or EOR, recovery rates and potential) available in MCGLADE (2013) and ROGNER (1997), and also the cost data from MCGLADE (2013) and IEA (2014), the following data were gathered, processed and compiled. Table 4-3 shows the resource availability for each region and oil category used in this study, and Table 4-4 shows the associated natural gas coefficient, in Nm^3 of gas per m^3 of oil.

The summary of the findings for oil resources are presented in Figure 4-2and Figure 4-3. Firstly, the regional aspect is highlighted, whilst in the second figure the typology of oil resources is shown.

Table 4-3 – Oil resource estimate for every region and category

	Oil (Bm³)																		
	Resources (Discovered)						Resources (Undiscovered)				EOR		Unconventional Oil						Total
	Onshore			Offshore			Onshore		Offshore		Onshore	Offshore	Shale Oil		Tar Sand Oil		Heavy Oil		
	P95	P50	P5	P95	P50	P5	P95	P50	P95	P50	P50	P50	TRR	Ad. TRR	TRR	Ad. TRR	TRR	Ad. TRR	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	
AFR	2.1	5.2	7.1	3.2	9.0	10.8	0.9	1.1	1.4	1.8	2.8	6.3	6.1	22.5	0.3	1.8	0.0	0.0	82.3
AUS	0.0	0.0	0.0	0.2	0.7	1.2	0.0	0.0	0.0	0.0	0.0	0.3	2.8	19.2	0.0	0.0	0.0	0.0	24.6
BRA	0.0	0.0	0.0	1.3	6.7	13.1	0.0	0.0	0.3	0.3	0.0	3.0	0.8	5.7	0.0	0.0	0.0	0.0	31.3
CAM	0.4	1.2	1.8	1.0	4.1	8.1	0.1	0.1	0.3	0.3	0.6	2.3	2.1	11.3	0.0	0.0	0.0	0.0	33.8
CAN	0.1	0.1	0.1	0.1	0.3	0.4	0.1	0.1	0.1	0.1	0.1	0.2	1.4	6.6	27.1	92.5	0.0	0.0	129.3
CAS	0.5	1.3	2.2	1.1	3.7	6.0	0.1	0.1	0.3	0.3	0.6	2.2	0.0	0.0	6.7	14.4	0.0	0.4	40.0
CHN	0.4	1.5	2.4	0.1	0.3	0.0	0.8	0.8	0.2	0.1	1.0	0.5	5.1	27.1	0.0	0.1	0.1	0.3	40.8
EEU	0.1	0.5	0.8	0.9	10.6	19.1	0.0	0.0	0.1	0.0	0.3	4.9	2.0	6.3	0.0	0.0	0.0	0.4	46.2
IND	0.0	0.1	0.2	0.1	0.3	0.3	0.0	0.0	0.0	0.0	0.1	0.2	0.6	1.0	0.0	0.0	0.0	0.0	3.0
JAP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
KOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MEA	9.0	26.4	38.5	1.7	5.0	0.0	4.1	5.4	0.8	1.0	14.1	9.8	0.0	0.0	0.0	0.0	0.0	0.0	115.8
RAS	0.1	0.4	0.7	0.5	1.6	2.4	0.1	0.1	0.4	0.4	0.2	0.9	4.6	8.9	0.1	0.0	0.0	0.0	21.4
RUS	3.6	9.8	14.7	0.4	1.6	0.0	1.1	1.3	0.1	0.2	5.2	3.6	11.9	25.7	4.5	6.0	0.0	0.0	89.8
SAF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SAM	1.3	4.0	5.7	0.1	1.6	3.0	0.8	0.6	0.1	0.2	3.1	2.5	8.6	41.4	0.0	0.0	9.2	94.6	176.9
USA	1.6	1.8	2.5	0.1	0.7	1.3	0.9	0.8	0.0	0.0	1.8	1.7	0.0	0.0	0.0	2.6	0.0	0.1	16.1
WEU	0.0	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.7	0.0	0.0	0.0	0.0	1.8

Notes: P(X) relates to assurance levels of resources.

Table 4-4 – Associated Natural Gas for every resource category

	Assoc. Natural Gas (Nm³/m³)											
	Resources (Discovered)						Resources (Undiscovered)				EOR	
	Onshore			Offshore			Onshore		Offshore		Onshore	Offshore
	P95	P50	P5	P95	P50	P5	P95	P50	P95	P50	P50	P50
	A	B	C	D	E	F	G	H	I	J	K	L
AFR	43	31	30	50	36	43	31	32	31	32	31	35
AUS	73	48	39	73	50	55	32	37	32	37	48	50
BRA	40	32	29	41	34	31	225	223	225	223	41	43
CAM	48	35	29	48	38	41	45	48	45	48	35	39
CAN	20	13	12	101	82	99	58	75	58	75	29	81
CAS	49	34	31	67	51	52	57	86	57	86	38	54
CHN	40	39	37	16	11	13	17	20	17	20	32	14
EEU	32	26	23	37	28	23	16	20	16	20	26	28
IND	65	47	44	59	41	46	63	74	63	74	49	44
JAP	0	0	0	0	0	0	0	0	0	0	0	0
KOR	0	0	0	0	0	0	0	0	0	0	0	0
MEA	35	26	24	37	27	30	29	35	29	35	28	29
RAS	43	38	37	75	57	62	102	118	102	118	54	69
RUS	50	37	35	86	78	78	82	95	82	95	44	80
SAF	0	0	0	57	45	50	0	0	0	0	0	45
SAM	39	29	28	59	45	40	34	49	34	49	32	46
USA	48	35	29	48	38	41	35	40	35	40	36	38
WEU	49	47	36	33	26	31	61	73	61	73	48	28

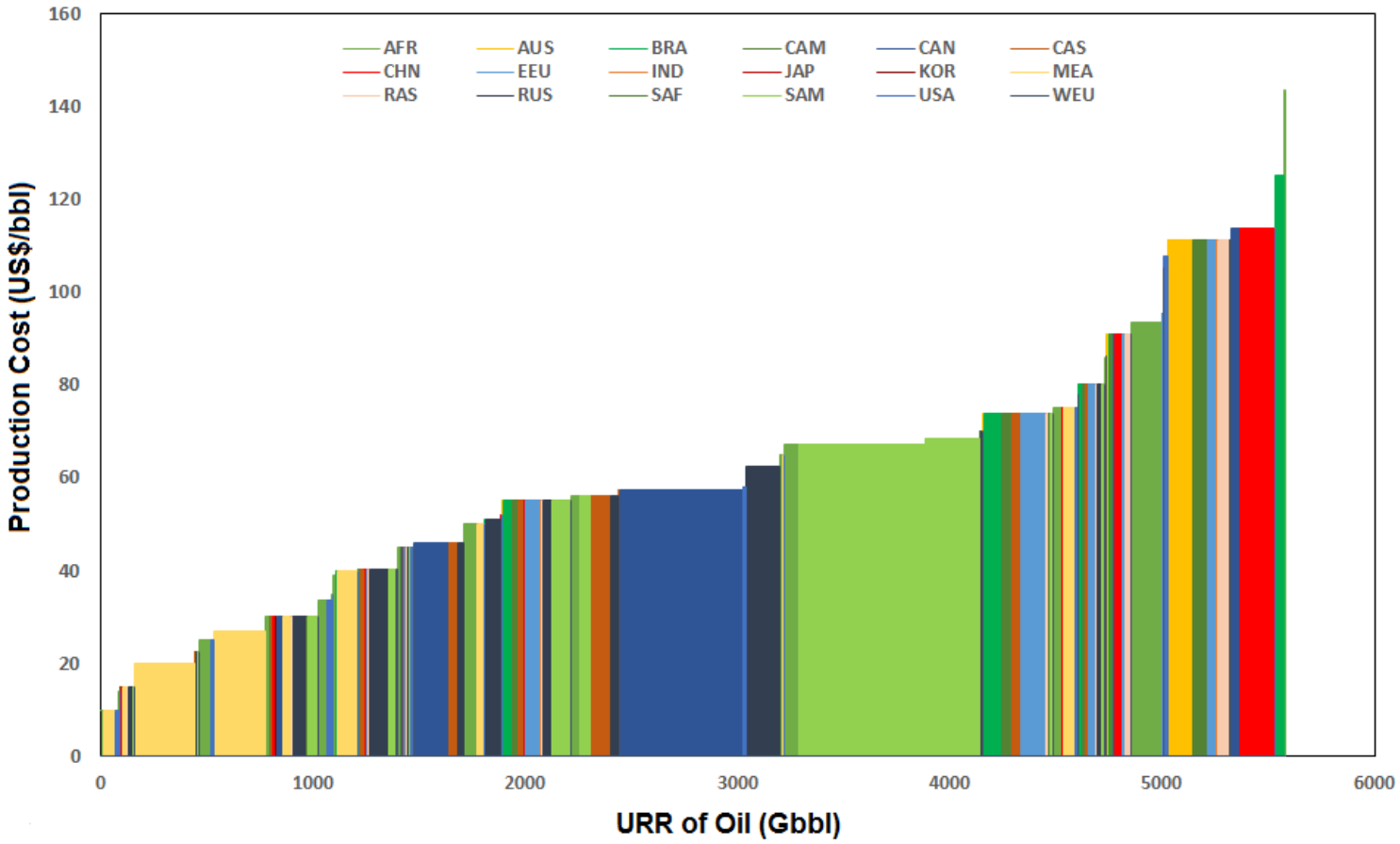


Figure 4-2 – Oil supply curve detailing each regional resource

Legend: URR - Ultimately Recoverable Resources

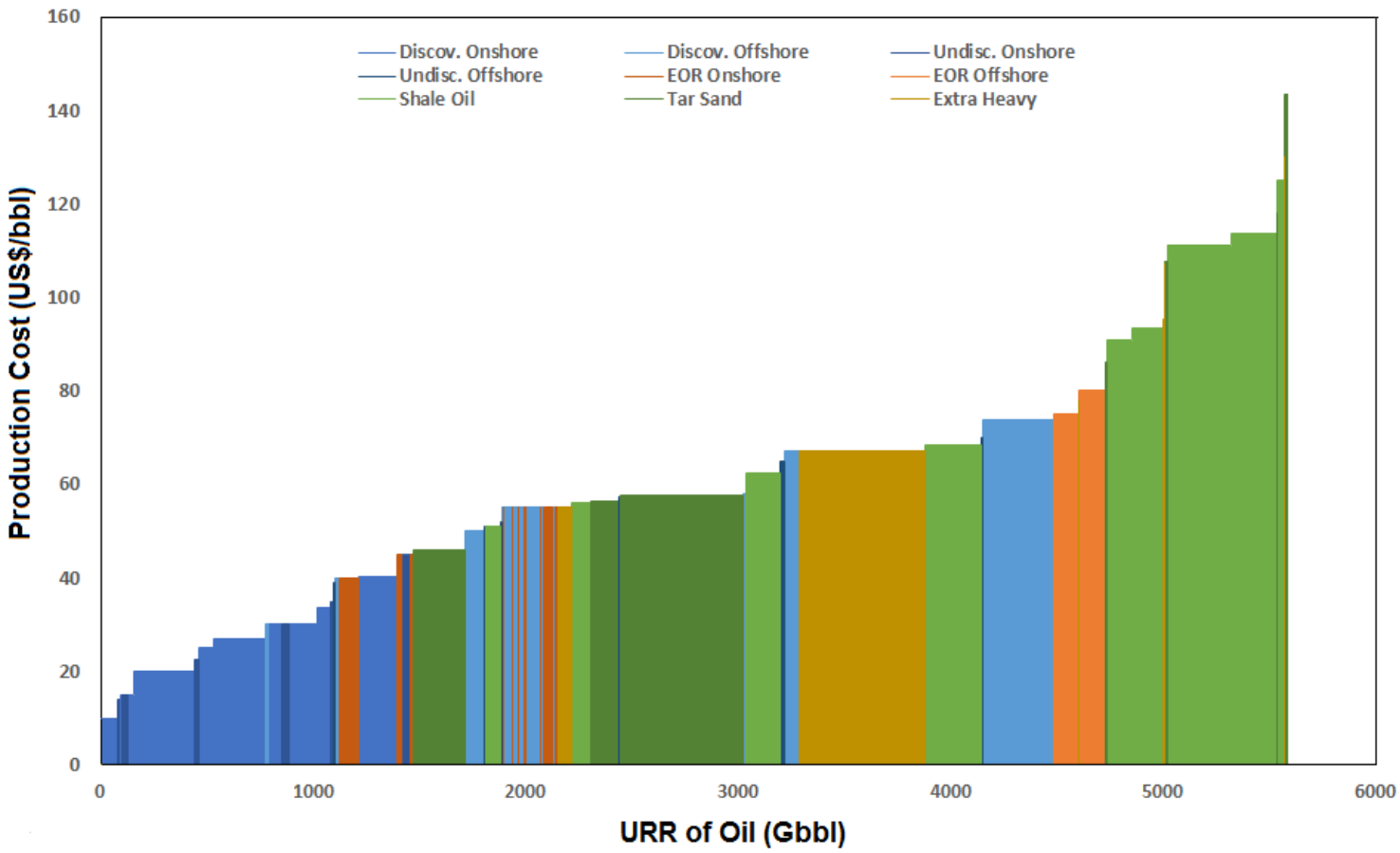


Figure 4-3 - Oil supply curve detailing each oil category

Legend: URR - Ultimately Recoverable Resources

The estimates in this study account for a total global resource of about 5,366 Gbbl of crude oil. This value is in good agreement with the available literature already described. However, the amount of available oil is not the only relevant information towards the development of a good supply curve for crude oil.

In order to evaluate the robustness and quality of the supply curve developed in this study, this curve was compared directly with those available in the literature, and are exposed in Figure 4-4 and Figure 4-5. The former compares the result with IEA (2014), which provides a simplified supply curve by type of resource. The latter compares the result with MCGLADE (2015), which in turn is an extremely detailed supply curve. As it can be seen, the developed data is in good agreement with the literature and within the ranges of both resource availability and production costs.

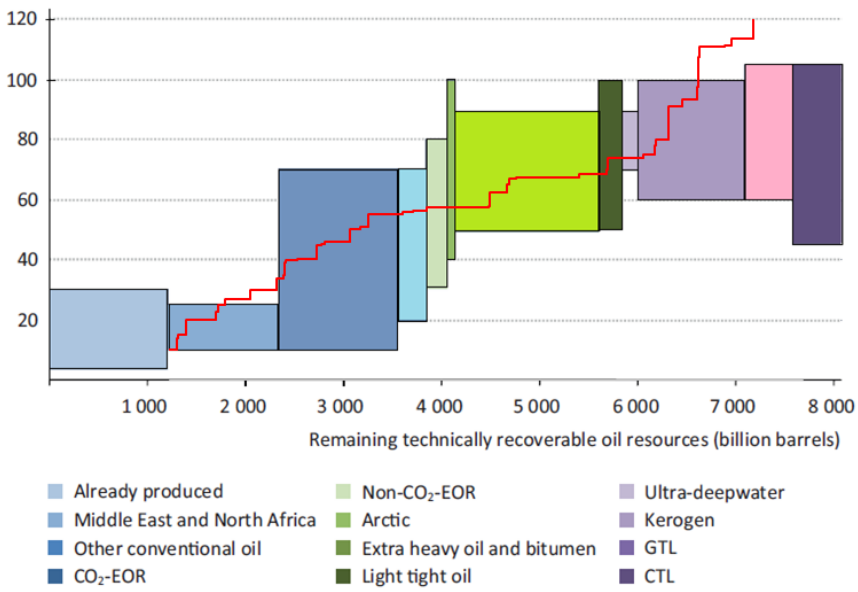


Figure 4-4 – Comparison between IEA (2014) and this study (red line)

Source: Adapted from IEA, 2014

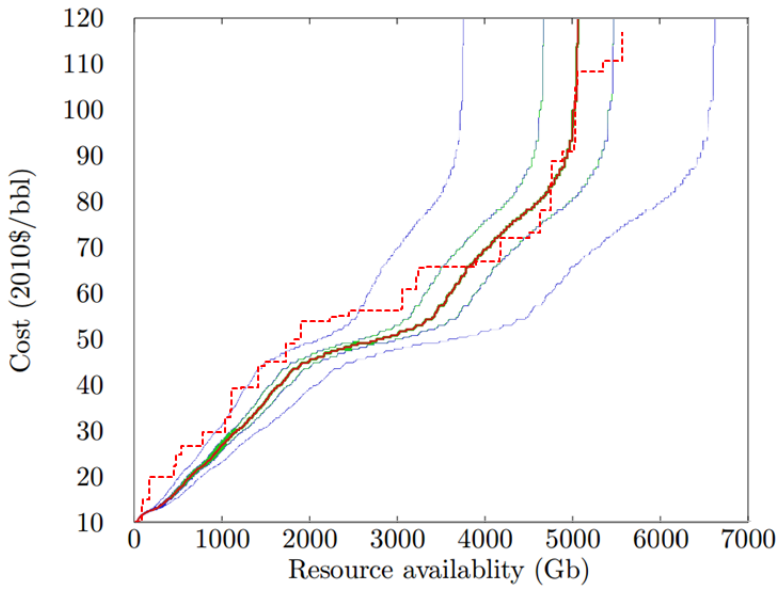


Figure 4-5 - Comparison between MCGLADE (2013) and this study (red line)

Source: Adapted from MCGLADE (2013)

4.2.Natural Gas and NGL resources

The second energy resource assessed in this thesis is the non-associated natural gas, which is the natural gas that can be extracted individually, without crude oil. In this type of resources, there may or may not be any condensate, or Natural Gas Liquids (NGL). The associated natural gas was estimated from the data from the previous section.

ROGNER (1997) also addresses natural gas resources, estimating an overwhelming 20,000 Gtoe, or roughly 22,000 TNm³, again with highlights to North America and Middle East. However, if one discounts the estimate for "Additional Occurrences" of unconventional resources, of which coal-bed methane and hydrates play a major role, this estimate is reduced to about 845 TNm³ of natural gas. This latter value is somewhat in line with MCGLADE (2013), whose calculation come up to about 680 TNm³ of natural gas.

This includes estimates for shale gas, which was taken from ARI (2013). This report evaluates the shale gas and shale oil resource in 26 regions, containing 41 individual countries profiles. Global shale gas resources are estimated around 420 TNm³, more relevantly for South America, North America and China. However, no estimates were found for NGL within shale gas resources throughout the world. Thus, this specific resource was not investigated further in this study, and should be revised in future studies.

Table 4-5 - Cost data for natural gas production

Gas category	Bound	Cost relationship	Cost (2010$/boe)	
			Min	Max
Reserves	Lower	Cost database (based on min IEA range)	11	29
	Upper	Cost database (based on max IEA range − finding cost)	22	40
Reserve growth	Lower	Upper reserves cost	22	40
	Upper	Upper reserves cost + $12/boe	34	52
Undiscovered	Lower	Lower reserve cost + regional finding cost	15	40
	Upper	Upper reserves cost + regional finding cost + $12/boe	40	63
DW reserves	Lower	Cost database (based on min IEA range)	27	32
	Upper	Cost database (based on max IEA range − finding cost)	38	42
DW reserve growth	Lower	Upper DW reserves cost	38	42
	Upper	Upper DW reserves cost + $12/boe	50	54
DW undiscovered	Lower	Lower DW reserve cost + US offshore finding cost	44	48
	Upper	Upper DW reserve cost + US offshore finding cost + $12/boe	67	71
Sour reserves	Lower	Cost database (based on min IEA range)	20	39
	Upper	Cost database (based on max IEA range − finding cost	31	50
Sour reserve growth	Lower	Upper sour reserves cost	31	50
	Upper	Upper sour reserves cost + $12/boe	43	62
Sour undiscovered	Lower	Lower sour cost + regional finding cost	24	50
	Upper	Upper sour cost + regional finding cost + $12/boe	49	73
Arctic gas	Lower	Min IEA range	22	22
	Upper	Max IEA range	65	65

Source: MCGLADE (2013)

Notes: DW means Deepwater.

The methodology and literature used for creating the natural gas supply curve in this study was basically the same as for the oil supply curve, since most of the literature relating to oil resource also deal with natural gas resources. The cost data, which had to be reorganized in order to adjust into the gas categories of this study, is presented in Table 4-5. The findings are shown in the following.

Table 4-6 – Natural gas resource estimate for every region and category

	Unassoc. Natural Gas (BNm³)													
	Resources (Discovered)						Resources (Undiscovered)						Unconventional	
	Onshore			Offshore			Onshore			Offshore			Shale Gas	
	P95	P50	P5	P95	P50	P5	P95	P50	P5	P95	P50	P5	TRR	Ad. TRR
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
AFR	809	1,163	1,773	836	1,773	2,985	1,528	1,206	2,306	1,578	1,840	3,881	27,188	29,111
AUS	29	54	56	792	1,776	2,631	4	3	3	109	98	162	12,236	19,693
BRA	1	2	3	620	2,422	4,473	1	0	1	665	633	1,149	6,860	10,975
CAM	45	139	265	315	868	2,450	26	47	50	185	296	460	15,260	19,162
CAN	175	218	332	11	22	39	487	277	1,230	30	28	144	16,044	20,886
CAS	1,713	3,888	6,394	735	2,023	3,272	760	592	1,290	326	308	660	0	0
CHN	448	1,130	2,012	17	48	92	820	1,008	2,008	30	43	92	31,220	41,786
EEU	353	574	886	633	5,960	11,802	59	12	29	106	128	393	11,256	11,110
IND	80	202	345	101	240	394	64	63	109	81	75	124	2,688	1,901
JAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MEA	6,918	13,926	19,978	2,010	3,325	4,877	1,876	2,380	4,453	545	568	1,087	0	0
RAS	573	1,079	1,697	1,138	2,651	4,284	289	299	568	574	734	1,433	8,064	5,694
RUS	2,149	4,643	7,589	5,196	13,404	22,965	553	619	1,337	1,338	1,787	4,046	7,980	10,217
SAF	0	0	0	11	37	85	0	0	0	0	0	0	10,920	8,890
SAM	743	1,477	2,395	177	1,159	2,423	429	408	816	102	320	825	33,208	44,238
USA	2,945	9,742	7,323	184	1,000	856	807	925	1,948	0	0	0	2,716	4,908
WEU	214	435	535	29	41	60	46	53	95	6	5	11	5,488	4,632

Table 4-7 - Associated NGL for every resource category

	NGL-to-NG Ratio (m³/kNm³)											
	Resources (Discovered)						Resources (Undiscovered)					
	Onshore			Offshore			Onshore			Offshore		
	P95	P50	P5	P95	P50	P5	P95	P50	P5	P95	P50	P5
	A	B	C	D	E	F	G	H	I	J	K	L
AFR	0.31	0.53	0.71	0.30	0.42	0.53	0.18	0.21	0.23	0.18	0.21	0.23
AUS	0.32	0.49	0.84	0.30	0.43	0.60	0.16	0.17	0.17	0.16	0.17	0.17
BRA	0.12	0.18	0.26	0.17	0.24	0.36	0.17	0.17	0.17	0.17	0.17	0.17
CAM	0.23	0.32	0.44	0.20	0.29	0.35	0.11	0.13	0.14	0.11	0.13	0.14
CAN	0.13	0.25	0.34	0.23	0.36	0.49	0.14	0.14	0.15	0.14	0.14	0.15
CAS	0.14	0.22	0.32	0.21	0.29	0.42	0.07	0.10	0.12	0.07	0.10	0.12
CHN	0.24	0.35	0.49	0.23	0.33	0.45	0.06	0.08	0.09	0.06	0.08	0.09
EEU	0.04	0.08	0.13	0.24	0.27	0.41	0.12	0.12	0.16	0.12	0.12	0.16
IND	0.05	0.08	0.12	0.13	0.17	0.24	0.08	0.09	0.12	0.08	0.09	0.12
JAP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
KOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	0.37	0.58	0.84	0.23	0.39	0.56	0.19	0.19	0.23	0.19	0.19	0.23
RAS	0.07	0.12	0.17	0.11	0.17	0.25	0.13	0.13	0.13	0.13	0.13	0.13
RUS	0.18	0.28	0.39	0.13	0.19	0.28	0.14	0.15	0.16	0.14	0.15	0.16
SAF	0.00	0.00	0.00	0.23	0.31	0.41	0.00	0.00	0.00	0.00	0.00	0.00
SAM	0.19	0.30	0.43	0.12	0.19	0.27	0.23	0.25	0.27	0.23	0.25	0.27
USA	0.13	0.25	0.34	0.23	0.36	0.49	0.15	0.15	0.15	0.15	0.15	0.15
WEU	0.13	0.26	0.46	0.04	0.08	0.12	0.14	0.15	0.20	0.14	0.15	0.20

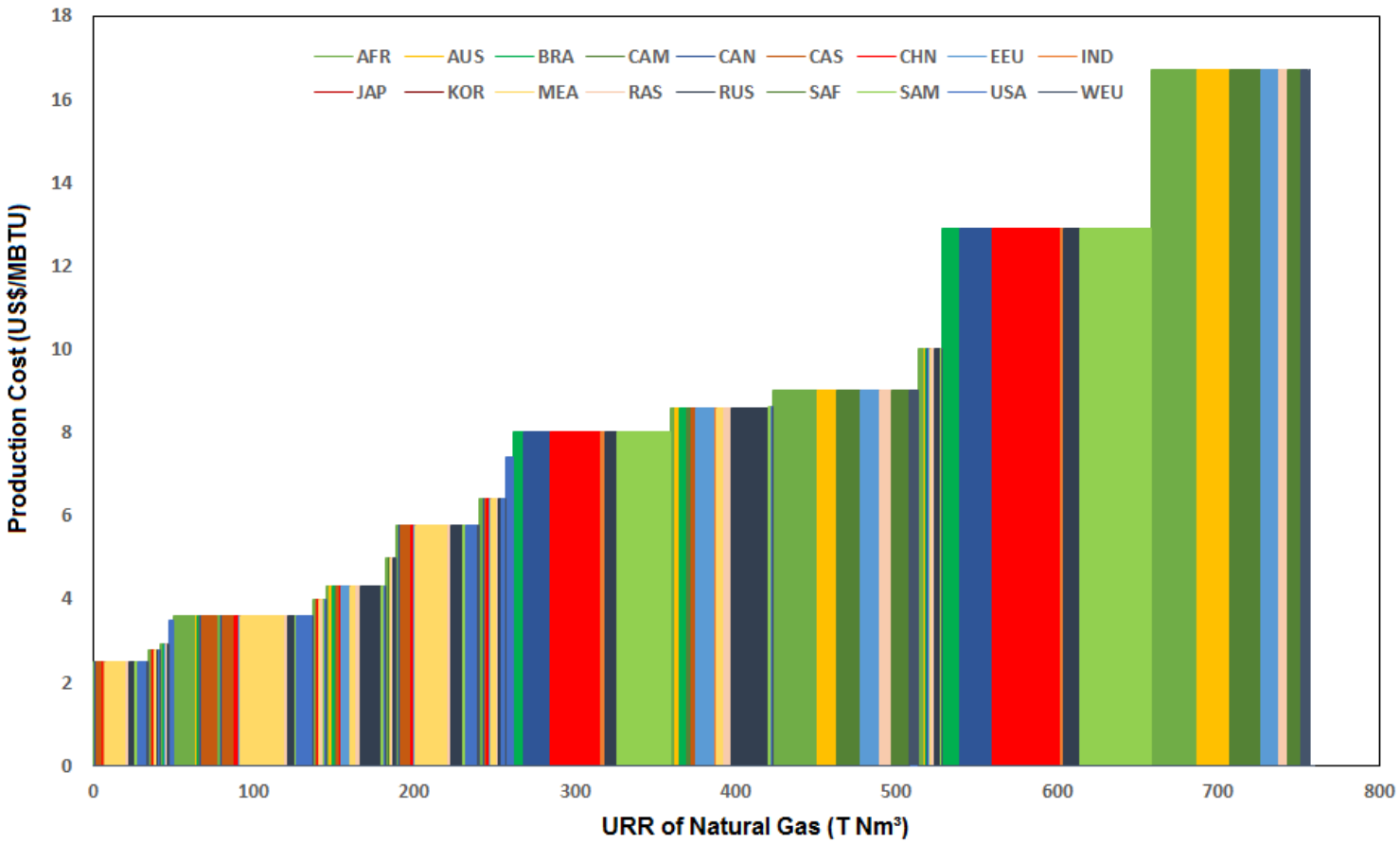


Figure 4-6 – Natural Gas supply curve detailing each regional resource

Legend: URR - Ultimately Recoverable Resources

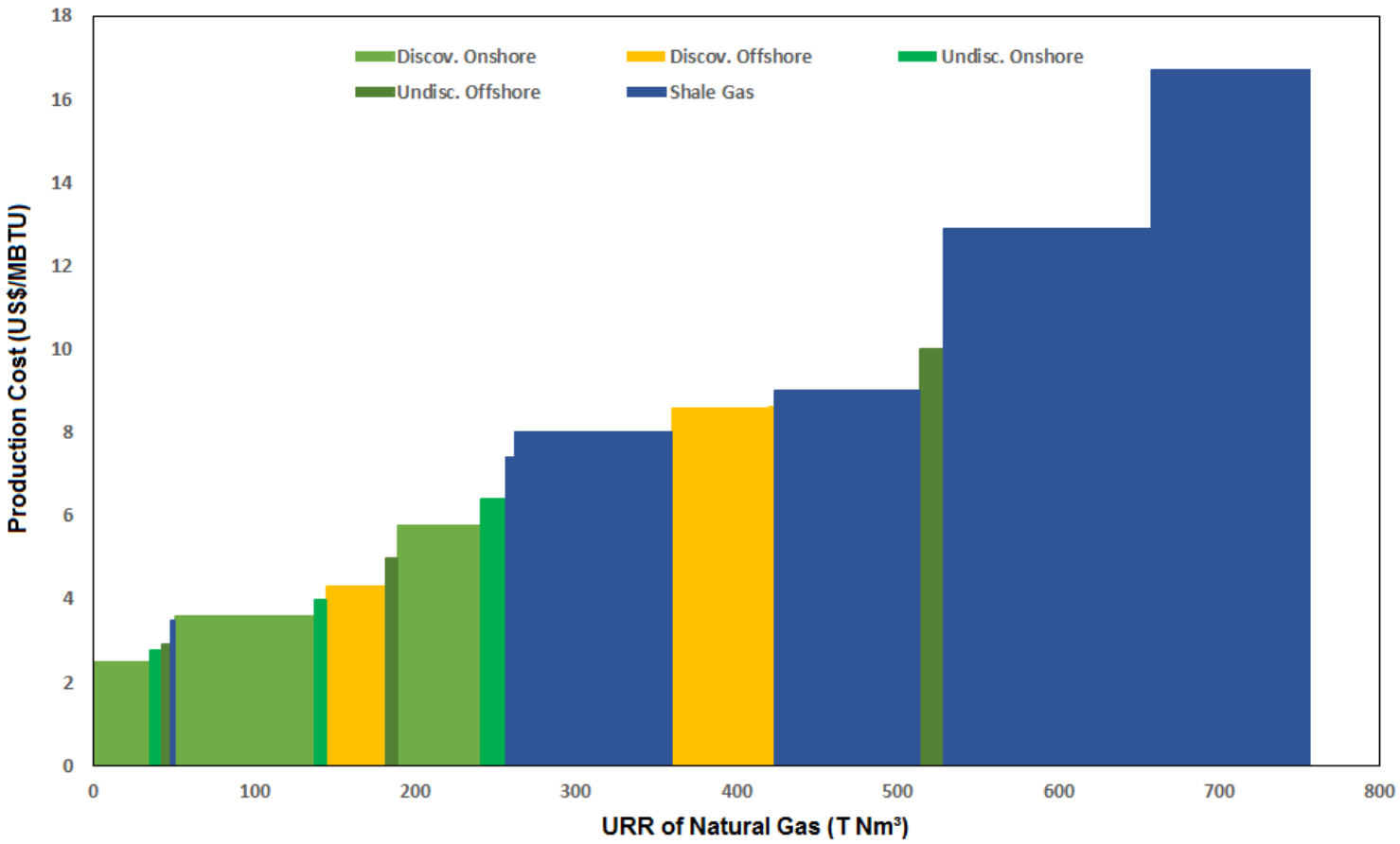


Figure 4-7 – Natural Gas supply curve detailing each category

Legend: URR - Ultimately Recoverable Resources

This study estimates the resource availability of natural gas resources in about 700 TNm³, roughly 3% higher than MCGLADE (2013) and MCGLADE AND EKINS (2015). By the way, Figure 4-8 compares the supply curve developed in this work with MCGLADE AND EKINS (2015). In this figure, it becomes clear that the total amount and general profile of the supply curve, even if relatively higher, is still in good agreement with each other.

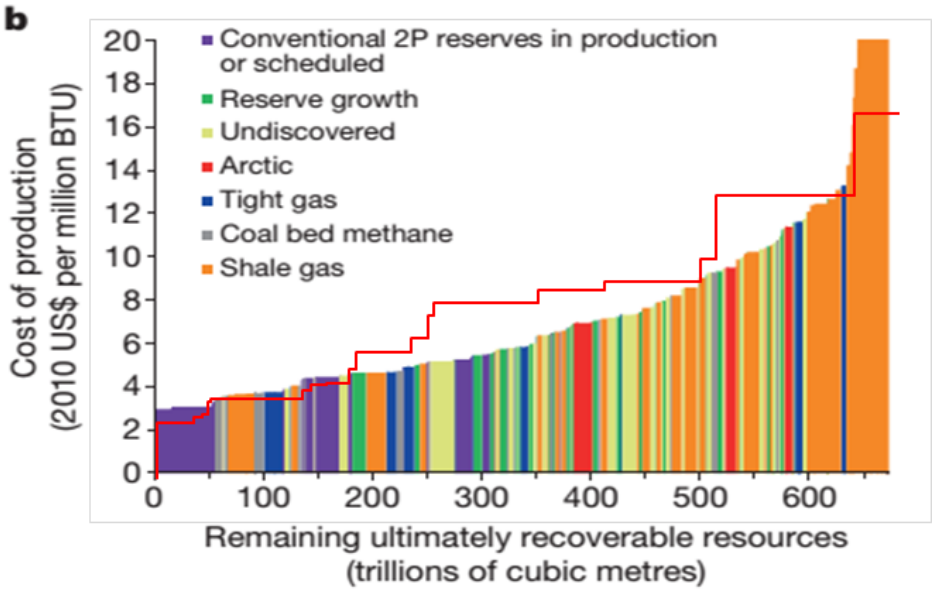


Figure 4-8 - Comparison of gas supply curve between MCGLADE AND EKINS (2015) and this study (red line)

Source: Adapted from MCGLADE AND EKINS (2015)

4.3. Coal resources

Coal resource assessment studies are very unlike oil and gas resource assessments: not only there are fewer studies available, but the findings of these studies are more convergent in terms of total value, probably due to the different methodologies for estimating solid resources.

The main sources of information for developing a specific supply curve for this study were ROGNER (1997), as it deals with hydrocarbons in general, WEC (2013), IEA (2014), MCGLADE AND EKINS (2015) and GMI (2015).

WEC (2013) provides estimates for proved, probable and possible resources of bituminous, sub-bituminous and lignite coal for several individual countries.

WEC (2013) and GMI (2015) provide information on the availability of the resources (surface or underground) for a few countries. Thus, whenever this information was lacking for a certain country or region, the approach used in this study was to use a nearer estimate available. For instance, the values for Africa (AFR) were based on data for South Africa (SAF), and so on.

Another important information available in GMI (2015), besides the country profiles of production and resources for 37 countries, include the estimates for coal bed methane potential and methane emissions. The report is part of the Global Methane Initiative (GMI), which is an international cooperation to promote the development of projects that recover and use methane as a clean energy source.

The data in this report were used to estimate the potential for coal bed methane recovery potential and to estimate methane emissions from coal production with recovery technologies.

The main limitation of this methodology is that the coefficients generated from GMI (2015) do not necessarily apply to the resource categories used in this study. That being said, the coefficients estimated in this study were used for other resource categories.

For instance, the same coefficient was used for a proven resource and probable resource of bituminous coal. The same happens with data for a given region, which were estimated by single country information within the region. An interesting case happens in Kazakhstan, part of Caspian (CAS) region, where the estimates suggest an increase of methane content for unexplored resources GMI (2015).

Table 4-8 - Coal resource estimate for every region and category

	Betuminous (EJ)							Sub-Betuminous (EJ)							Lignite (EJ)				
	Reserve		Res. 2P Rec		Res 3P	URR 1P	URR 3P	Reserve		Res. 2P Rec		Res 3P	URR 1P	URR 3P	Reserve	Res. 2P Rec	Res 3P	URR 1P	URR 3P
	Surface	Mining	Surface	Mining	Mining	Mining	Mining	Surface	Mining	Surface	Mining	Mining	Mining	Mining	Surface	Surface	Mining	Mining	Mining
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
AFR	17	17	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0
AUS	466	466	107	107	1673	427	1129	24	24	7	7	0	4	29	628	1040	1690	152	335
BRA	0	0	0	0	0	0	0	20	75	33	125	96	41	109	0	0	0	0	0
CAM	11	11	0	0	0	0	0	1	5	0	0	0	0	0	1	0	0	0	0
CAN	44	44	0	0	0	30	687	8	10	0	0	0	53	1302	37	0	0	196	1451
CAS	280	280	0	0	0	0	0	3	1	13	4	42	2	39	279	103	534	21	425
CHN	359	1201	0	0	0	0	0	521	183	0	0	0	0	0	311	0	0	0	0
EEU	71	71	11	11	82	355	1347	18	6	15	5	19	7	22	868	18	37	294	540
IND	1126	281	0	0	0	1247	4048	0	0	0	0	0	0	0	75	0	0	0	0
JAP	4	4	0	0	0	107	235	0	0	0	0	0	0	87	0	0	0	3	17
KOR	0	0	0	0	0	0	0	1	2	0	1	3	2	13	0	0	0	0	0
MEA	15	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RAS	40	40	11	11	0	74	172	52	18	0	0	0	189	623	72	0	0	79	172
RUS	283	948	0	0	0	0	0	1508	530	0	0	0	0	0	175	0	0	0	0
SAF	378	378	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAM	86	86	57	57	106	0	0	5	17	0	0	0	0	0	0	0	0	0	0
USA	751	1970	0	0	4703	3338	5769	882	1179	0	0	3414	1320	2187	505	0	5057	148	1483
WEU	200	200	0	0	0	0	1	262	92	0	0	0	2	3	317	0	0	117	0

Table 4-9 – Cost data for coal extraction

Betuminous (US$/t)							Sub-Betuminous (US$/t)							Lignite (US$/t)				
Reserve		Res. 2P Rec		Res 3P	URR 1P	URR 3P	Reserve		Res. 2P Rec		Res 3P	URR 1P	URR 3P	Reserve	Res. 2P Rec	Res 3P	URR 1P	URR 3P
Surface	Mining	Surface	Mining	Mining	Mining	Mining	Surface	Mining	Surface	Mining	Mining	Mining	Mining	Surface	Surface	Mining	Mining	Mining
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
65	75	85	95	120	180	220	50	60	85	120	145	160	190	25	30	60	80	160

Source: Adapted from WEC (2013)

Table 4-10 – Methane content for every resource category

	Betuminous (m³CH4/t)							Sub-Betuminous (m³CH4/t)							Lignite (m³CH4/t)				
	Reserve		Res. 2P Rec		Res 3P	URR 1P	URR 3P	Reserve		Res. 2P Rec		Res 3P	URR 1P	URR 3P	Reserve	Res. 2P Rec	Res 3P	URR 1P	URR 3P
	Surface	Mining	Surface	Mining	Mining	Mining	Mining	Surface	Mining	Surface	Mining	Mining	Mining	Mining	Surface	Surface	Mining	Mining	Mining
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
AFR	2.2	29.3	2.2	29.3	29.3	29.3	29.3	2.2	29.3	2.2	29.3	29.3	29.3	29.3	2.2	2.2	29.3	29.3	29.3
AUS	2.8	9.9	2.8	9.9	9.9	9.9	9.9	2.8	9.9	2.8	9.9	9.9	9.9	9.9	2.8	2.8	9.9	9.9	9.9
BRA	2.6	22.2	2.6	22.2	22.2	22.2	22.2	2.6	22.2	2.6	22.2	22.2	22.2	22.2	2.6	2.6	22.2	22.2	22.2
CAM	3.0	14.1	3.0	14.1	14.1	14.1	14.1	3.0	14.1	3.0	14.1	14.1	14.1	14.1	3.0	3.0	14.1	14.1	14.1
CAN	0.9	14.4	0.9	14.4	14.4	14.4	14.4	0.9	14.4	0.9	14.4	14.4	14.4	14.4	0.9	0.9	14.4	14.4	14.4
CAS	9.5	19.5	9.5	29.0	33.0	33.0	33.0	9.5	19.5	9.5	29.0	33.0	33.0	33.0	9.5	9.5	19.5	19.5	19.5
CHN	0.6	6.5	0.6	6.5	6.5	6.5	6.5	0.6	6.5	0.6	6.5	6.5	6.5	6.5	0.6	0.6	6.5	6.5	6.5
EEU	0.7	11.0	0.7	11.0	11.0	11.0	11.0	0.7	11.0	0.7	11.0	11.0	11.0	11.0	0.7	0.7	11.0	11.0	11.0
IND	0.3	21.5	0.3	21.5	21.5	21.5	21.5	0.3	21.5	0.3	21.5	21.5	21.5	21.5	0.3	0.3	21.5	21.5	21.5
JAP	10.9	27.0	10.9	27.0	27.0	27.0	27.0	10.9	27.0	10.9	27.0	27.0	27.0	27.0	10.9	10.9	27.0	27.0	27.0
KOR	10.9	27.0	10.9	27.0	27.0	27.0	27.0	10.9	27.0	10.9	27.0	27.0	27.0	27.0	10.9	10.9	27.0	27.0	27.0
MEA	1.4	6.9	1.4	6.9	6.9	6.9	6.9	1.4	6.9	1.4	6.9	6.9	6.9	6.9	1.4	1.4	6.9	6.9	6.9
RAS	0.3	7.1	0.3	7.1	7.1	7.1	7.1	0.3	7.1	0.3	7.1	7.1	7.1	7.1	0.3	0.3	7.1	7.1	7.1
RUS	7.6	15.0	7.6	15.0	15.0	15.0	15.0	7.6	15.0	7.6	15.0	15.0	15.0	15.0	7.6	7.6	15.0	15.0	15.0
SAF	0.5	3.7	0.5	3.7	3.7	3.7	3.7	0.5	3.7	0.5	3.7	3.7	3.7	3.7	0.5	0.5	3.7	3.7	3.7
SAM	6.0	14.1	6.0	14.1	14.1	14.1	14.1	6.0	14.1	6.0	14.1	14.1	14.1	14.1	6.0	6.0	14.1	14.1	14.1
USA	1.3	14.4	1.3	14.4	14.4	14.4	14.4	1.3	14.4	1.3	14.4	14.4	14.4	14.4	1.3	1.3	14.4	14.4	14.4
WEU	0.1	20.6	0.1	20.6	20.6	20.6	20.6	0.1	20.6	0.1	20.6	20.6	20.6	20.6	0.1	0.1	20.6	20.6	20.6

Finally, the findings of this study are presented in Table 4-8, Table 4-9 and Table 4-10. The former presents the resources by type of coal, category and region of this study. The latter shows the best-guess estimates for methane content in coal beds.

As for the supply curve, Figure 4-9 presents a comparison between this study's estimate and the literature. It can be observed that for coal, the estimated curve is much more closely correlated with the literature, as previously mentioned.

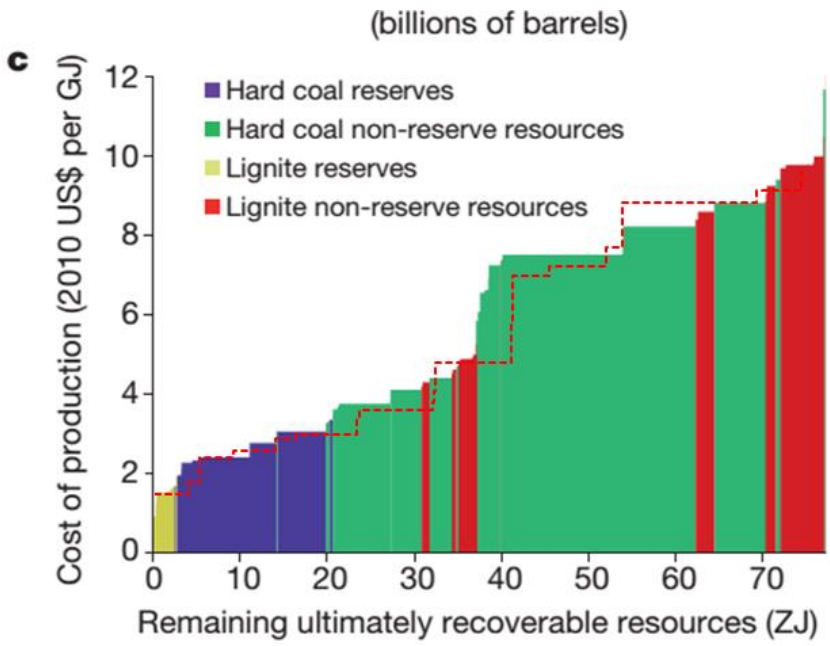


Figure 4-9 - Comparison of coal supply curve between MCGLADE AND EKINS (2015) and this study (red line)

Source: Adapted from MCGLADE AND EKINS (2015)

4.4. Uranium Resources

Uranium, for use in nuclear power, is the only exhaustible resource assessed in this study that is not a fossil fuel. Just as happened with coal (and many other solid resources), the estimates available in the literature for uranium resources are a lot more comprehensive and agreeable then that of oil and gas.

For uranium this is even more so true, due to the national and international interest in mapping the location and accessibility of the nuclear resources, due to risk of exposure to natural radiation and potential proliferation of non-energetic nuclear technologies.

For instance, WEC (2013), IAEA (1999) and IAEA (2014) provide a summary of national reports, which includes resource assessment of natural uranium. All these studies used the IAEA classification for uranium resources, which are directly correlated to extraction costs (IAEA, 2014).

The resources are divided into two aspects, extraction costs and resource nature, which are: identified (Discovered) resources; Inferred resources; Prognostic (Undiscovered) resources; and Speculative (Undiscovered) resources. The cost categories are steps of costs lower than 40, 80, 130 and 160 US$/kgU extracted.

By aggregating national inventories by the regions of the model, Figure 4-10 was created, in which a global supply curve for uranium is presented. Despite the available literature and robust estimates, another figure such as this was not found in the literature for comparison.

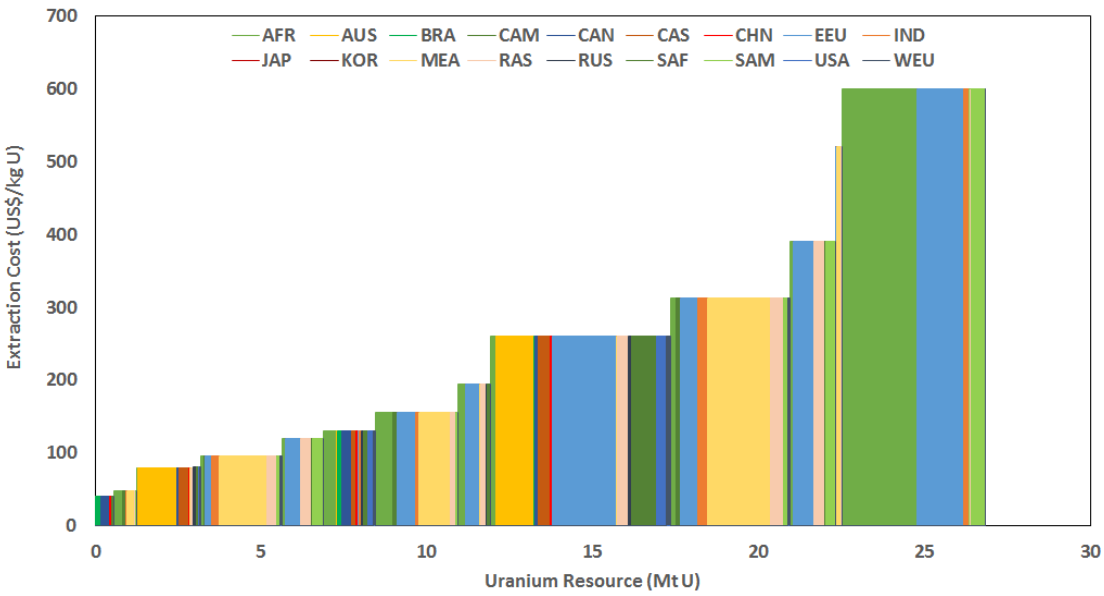


Figure 4-10 – Global supply curve for uranium

Source: Data adapted from WEC (2013) and IAEA (2014)

4.5.Hydro Energy

The next energy resource is the first renewable and the most important primary energy for electricity generation in Brazil: Hydropower. Even though hydropower resources are of great importance and are widely assessed in Brazil, this is not the case for other countries and regions.

In fact, when compared to other renewable resources, such as wind, solar and bioenergy, there are relatively fewer studies and reports assessing hydro resources for a group of countries. Moreover, as it will be shown, even in studies where there are assessments of total hydro potential, the quality of the resources is not detailed (WEC, 2013).

For hydro, the quality of the resources derives from two major components: capacity factors and resource availability. The latter is primarily associated with resources location, which can be associated to the distance from main consumers, dispersion of resources (rivers) in the territory, and the land cover that can be affected by building a new hydro plant. For Brazil, amongst these aspects, the latter is the most important limiting factor for the exploitation of Hydro power resources.

All the aspects presented above are directly associated with exploitation costs. Thus, the total resources can be separated in terms of costs in order to create a supply curve for Hydro power, just like those presented for oil, gas and coal.

Unfortunately, this type of information was not found in the literature for global resources. The only available information of this kind was provided by the International Renewable Energy Agency (IRENA). In both IRENA (2014a) and IRENA (2012) several regional profiles for hydro projects are presented, but from the IRENA database, the unexploited potential was used and condensed in a single supply curve for Hydro, as show in Figure 4-11.

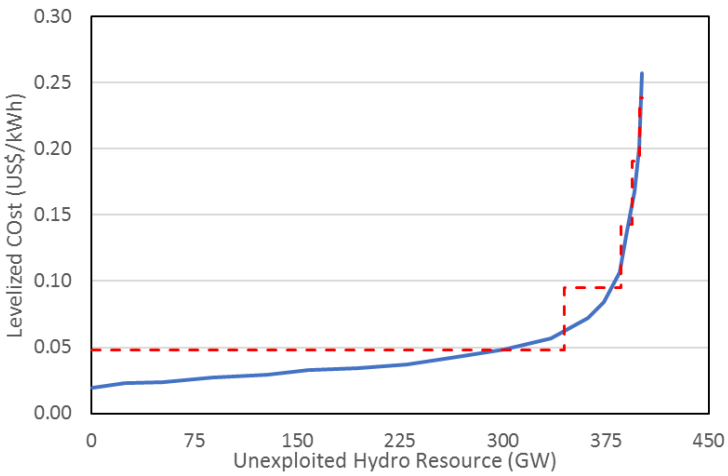


Figure 4-11 – Unexploited hydro profile

Legend: original data in blue, stepped function in dashed red line.

Source: Adapted form IRENA (2014a)

In the figure, the blue line is the original data, and the dashed red line represents the discrete stepped curve used to simplify the profile. As such, the discrete profile was used to estimate a supply curve for the total resource assessed in the literature (IRENA, 2012; WEC, 2013). WEC (2013) provides resource estimates for 168 countries, which were used to be aggregated into the 18 regions of this study. Only the exploitable resources were used to assess total hydro potential, which was estimated at near 4.900 GW, globally. Table 4-11 presents the estimated potential by each region and the type of hydro (large and small).

Table 4-11 – Estimated installed capacity, total potential and potential by category (GW)

Region	Installed Capacity	Total Potential	Large Hydro Potential					Small Hydro Potential				
			Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5	Categ. 1	Categ. 2	Categ. 3	Categ. 4	Categ. 5
AFR	31	439	301	36	7	5	2	75	9	2	1	0
AUS	18	71	49	6	1	1	0	12	1	0	0	0
BRA	84	265	182	22	4	3	1	46	5	1	1	0
CAM	15	105	72	9	2	1	0	18	2	0	0	0
CAN	98	161	110	13	2	2	1	28	3	1	0	0
CAS	28	257	176	21	4	3	1	44	5	1	1	0
CHN	48	735	505	60	11	8	3	126	15	3	2	1
EEU	140	430	295	35	7	5	2	74	9	2	1	0
IND	78	217	149	18	3	2	1	37	4	1	1	0
JPN	32	51	35	4	1	1	0	9	1	0	0	0
KOR	7	7	5	1	0	0	0	1	0	0	0	0
MEA	18	457	314	38	7	5	2	78	9	2	1	0
RAS	30	437	300	36	7	5	2	75	9	2	1	0
RUS	92	461	316	38	7	5	2	79	9	2	1	0
SAF	3	12	8	1	0	0	0	2	0	0	0	0
SAM	52	350	240	29	5	4	1	60	7	1	1	0
USA	155	407	279	33	6	4	2	70	8	2	1	0
WEU	17	39	27	3	1	0	0	7	1	0	0	0

4.6. Solar and Wind Energy

Solar and Wind energy resources were estimated from data mostly from NREL (2015), with additional information from WEC (2013) and NREL (2015b, 2015c), especially for cost estimation.

NREL (2015) provides supply curves for each energy source, based on a resource assessment performed at the National Renewable Energy Laboratory (NREL) based on the National Center for Atmospheric Research's (NCAR) Climate Four Dimensional Data Assimilation (CFDDA) mesoscale climate database. The data are provided for 184 countries. However, the type of data available for Solar and Wind energy are slightly different

In terms of solar potential, it is important to differentiate Diffuse and Direct solar radiation. The full solar potential is used to estimate solar photovoltaics potential, whilst only the latter is used to estimate Concentrating Solar Power (CSP) potential. For each of the types of radiation, NREL (2015) provides a separation of the incident radiation by capacity factor, which represents the availability of the solar resource itself. This is the only aspect that is being considered to differentiate cost in a supply curve for solar resource. It is worth noting that the electricity generation technologies can influenciate the oerall capacity factor, for istance, with power and thermal storage.

Additionally, since the actual potential in terms of power depends strongly on the technology used, especially for CSP, the supply curve introduced in the model was based on solar radiance itself, instead of on electricity or power.

Therefore, the supply curve for each region was based on the sum of the potential of available countries. However, the original data separated resources in ten steps of increasing capacity factor, and this study simplified it to only four steps. This was done to take some stress out not only from inputting data into the model, but also from the model itself, making it lighter and faster. The categories used are show in Figure 4-12.

As for wind resources, NREL (2015) provides the same information (country profiles with 9 steps of capacity factor for the resources), but with two additional information: separation between onshore and offshore wind potentials; distance from major consumer (for onshore) and from the coastline (for offshore). Additionally, for offshore, the water depth was also presented.

This new information for wind is extremely helpful in creating better supply curves for energy resources, since the optimum decision from the model may be to use a lower capacity factor that is closer to the end consumer, depending on the costs associated with both aspects.

Again, just as for Solar, the supply curve available in NREL (2015) was simplified to go into the model. From the 27 steps for onshore wind, between capacity factor and distance, a 12 step curve was estimated. As for offshore, out of 81 step function, (combining capacity factor, distance to shore and water depth) a new 27 step discrete curve was created. Figure 4-12 also presents the categories used in the supply curves used in this study.

Offshore Categories	
Water Depth	Distance
Shallow	100 km
Shallow	200 km
Shallow	1500 km
Transitional	100 km
Transitional	200 km
Transitional	1500 km
Deep	100 km
Deep	200 km
Deep	1500 km

Wind Average C.F.*	
Original	New Steps
18%	20%
20%	
24%	
28%	30%
32%	
36%	38%
40%	
44%	44%
46%	

Solar Average Radiation (KWh/m²/d)	
Original	New Steps
< 3	3.25
3.0 - 3.5	
3.5 - 4.0	4.5
4.0 - 4.5	
4.5 - 5.0	
5.0 - 6.25	6.25
6.25 - 7.25	
7.25 - 7.5	7.5
7.5 - 7.75	
> 7.75	

Onshore Caterogies
Distance
100 km
200 km
1500 km

*C.F.: Capacity factor categories for both onshore and offshore wind.

Figure 4-12 – Wind and Solar resource categories

Source: data adapted from NREL (2015)

4.7. Carbon Transportation and Storage

The last "resource" assessed in this chapter is not an energy resource *per se*, but it is definitely energy related. It comprehends the assessment of the potential for underground storage potential for carbon dioxide. Storage is the last step of Carbon Capture and Storage (CCS), and involves finding a location or a way to store carbon dioxide, which was previously captured (separated and purified) from carbon sources.

Several studies address the importance of CCS in achieving GHG emission reduction, by either capturing carbon from fossil sources (Fossil CCS) or bioenergy sources (BioCCS, or BECCS) (AZAR *et al*., 2010; IEA-GHG, 2011; KRIEGLER *et al*., 2014).

Nonetheless, there is not a lot of literature on detailed assessment of the amount of reservoir capacity for carbon storage. There are general estimates, such as: KETZER *et al.* (2007) for Brazil; BRENNAN *et al.* (2010), NETL (2012) and BLONDES *et al.* (2013) for the United States; BENTHAM (2006) for the North Sea; GAMMER *et al.* (2011) for the United Kingdom; IEA-GHG (2008b) for India; Li (2007) for China; CLOETE (2010) for South Africa; IEA-GHG (2004), IPCC (2005) and IEA-GHG (2008) for global estimates.

The range of estimates from these studies is large, from 200 to 56,000 $GtCO_2$, reflecting both the different assumptions used to make these estimates and the uncertainty in the parameters (IPCC, 2005).

The methodology used in this study differentiates between Enhanced Oil Recovery (EOR), Gas Fields and Saline Aquifers.

For EOR, the potential was calculated from the amount of oil available for EOR, as shown in Table 4-3, with carbon storage coefficient (in tCO2/bbl produced) from the literature. This coefficient varied between 0.27 to 0.32 tCO2/bbl across regions, according to IEA-GHG (2009a).

As for gas fields, the procedure was basically the same as for EOR, but the gas fields in Table 4-6 were used. The coefficient for carbon storage was estimated from IEA-GHG (2009b), and varied from 2.3 to 2.9 tCO2/kNm³.

The last storage option, saline aquifers, has the highest storage potential, but there are many uncertainties regarding the extent to which the potential capacity can become usable storage (IEA-GHG, 2008). Figure 4-13 presents the theoretical storage capacity per region estimated in IEA-GHG (2008). The same report also addresses detailed

information on saline aquifers for nine regions out of the 18 that make up the model developed in this study.

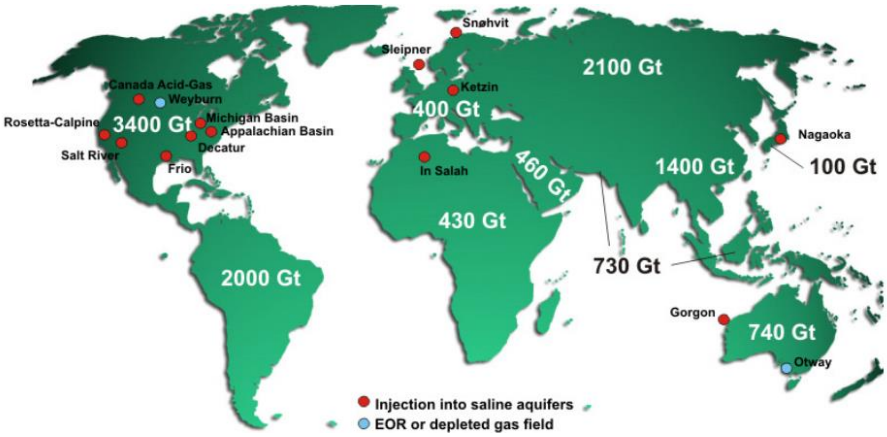


Figure 4-13 – Theoretical carbon storage capacity estimates

Source: IEA-GHG, 2008

The first set of results for the carbon storage analysis is shown in Table 4-12. Also, the global values estimated in this study are compared with the data available in IEA-GHG (2008, 2009a, 2009b). It is worth noting that the estimates from this study are consistent with the EOR and gas production potential, already described. Not only that, but the data used in this analysis are able to differentiate between onshore and offshore potential for storage in EOR and Gas Fields.

In order to estimate the potential storage capacity in saline aquifers, data from IEA-GHG (2008) was used only when no country specific data was available. Furthermore, the disaggregation between onshore and offshore aquifers was determined by the ratio of onshore and offshore potential in oil and gas fields, since there was no available data in the analysed reports. The premise is that the geological formations, even if different by structure and composition, are probabilistically more keen on having the same distribution. It is, with doubt, a controversial, but necessary, assumption.

Table 4-12 – Carbon Storage potential for every category and region

	EOR		Gas Fields		LowCost Aquifer		HighCost Aquifer	
	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore
AFR	5	12	20	30	94	94	111	111
AUS	0	1	0	16	70	630	4	36
BRA	0	6	0	23	87	780	113	1020
CAM	1	5	1	11	4	40	5	47
CAN	0	0	7	1	264	88	711	237
CAS	1	4	34	17	30	10	36	12
CHN	2	1	20	1	803	268	273	91
EEU	1	9	5	50	2	17	5	46
IND	0	0	2	2	75	75	75	75
JAP	0	0	0	0	15	15	36	36
KOR	0	0	0	0	4	4	5	5
MEA	27	18	114	29	158	53	187	62
RAS	0	1	13	31	56	56	66	66
RUS	9	6	44	128	481	481	569	569
SAF	0	0	0	0	0	1	2	17
SAM	6	5	15	12	88	88	104	104
USA	3	3	62	5	426	142	1149	383
WEU	0	0	4	0	64	21	176	59
Total	55	71	341	356	2722	2863	3627	2974
	127		**698**		**12186**			
IEA-GHG	**139**		**672**		**11680**			

Each of the eight categories for carbon storage is attributed to a common cost of injection. That means that there is no regional distinction between injection costs. The costs considered for injection are available in Figure 4-14.

Injection Costs (US$/tCO2)							
EOR		Gas Fields		LowCost Aquifer		HighCost Aquifer	
Onshore	Offshore	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore
3	6	4	10	5	7	12	14

Transportation Costs					
Data	Unit	Distance (km)			
		100	500	1000	2000
Inv	US$/tCO2	15.7	80.4	175.0	304.6
Fom	US$/tCO2/y	0.09	0.44	0.87	1.62
Elect	MWh/tCO2/y	0.0	2.2	9.8	16.0

Figure 4-14 – Cost data for injection (above) and transportation (below) of carbon dioxide
Source: Adapted from IEA-GHG (2008, 2009a, 2009b, 2011)

Another important stage of CCS, which can result in a considerable fraction of the cost associated with CO_2 storage is the transportation stage. Depending on the distance and the type of terrain where the CO_2 must pass, the costs associated with transportation can easily overcome the injection costs.

In order to estimate transportation costs, an analysis was made using a Geographic Information System (GIS) environment to estimate average distance between carbon

storage reservoirs and main emissions sources. The location of major urban agglomerations was used as a proxy for emissions sources. As for the destination, the location of the main oil and gas fields around the world was used.

Since there was no available global information in GIS found for aquifers in the literature and a comprehensive GIS database, the distance profile for oil and gas fields was used for aquifers as well. Whenever possible, GIS was used to generate up to 5 random points near major urban agglomerations and 5 points within oil and gas fields, for a single region. Then, the distance matrix was calculated. By this method, the mean distance and deviation was calculated, and the profile was determined.

The only exceptions were Japan (JPN) and South Korea (KOR), for which no data were available. The procedure was, then, to estimate an average distance based on south Asian countries, like Indonesia and Philippines.

In order to simplify the manipulation of data inside the model and simplify calculation time within the model, four standard steps for distance were used for all regions: 100 km; 500 km; 1,000km; and over 2,000 km. This study could not find a more comprehensive assessment of the underground CO_2 storage potential supply curve in the literature.

Table 4-13 – Estimated resource distribution for carbon transportation and storage, for every region

	Storage Capacity (GtCO2)															
	EOR								Gas Fields							
	Onshore				Offshore				Onshore				Offshore			
	Distance (km)				Distance (km)				Distance (km)				Distance (km)			
	100	500	1000	2000	100	500	1000	2000	100	500	1000	2000	100	500	1000	2000
AFR	0.3	0.8	0.5	3.6	0.6	1.8	1.2	8.2	1.0	3.0	2.0	14.2	1.5	4.5	3.0	20.8
AUS	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.3	0.1	0.0	0.1	0.2	2.4	1.6	4.0	8.1
BRA	0.0	0.0	0.0	0.0	1.5	1.5	2.7	0.3	0.0	0.0	0.0	0.0	5.8	5.8	10.4	1.2
CAM	0.1	0.5	0.1	0.5	0.2	2.1	0.5	1.9	0.1	0.6	0.1	0.5	0.5	4.8	1.1	4.2
CAN	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.2	0.4	0.7	2.1	3.9	0.0	0.1	0.2	0.4
CAS	0.3	0.1	0.6	0.2	0.9	0.2	2.1	0.6	8.4	1.7	18.6	5.1	4.2	0.8	9.3	2.5
CHN	0.1	0.3	0.8	0.4	0.0	0.2	0.5	0.2	1.0	3.9	9.8	4.9	0.0	0.2	0.4	0.2
EEU	0.1	0.2	0.2	0.1	1.8	3.1	2.7	1.3	1.0	1.8	1.5	0.8	10.0	17.5	15.0	7.5
IND	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.7	0.5	0.6	0.2	0.8	0.6	0.7
JAP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
KOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MEA	2.7	11.9	8.0	4.0	1.8	8.3	5.5	2.8	11.4	51.4	34.3	17.1	2.9	12.9	8.6	4.3
RAS	0.0	0.0	0.0	0.3	0.1	0.1	0.1	1.1	0.7	1.3	1.3	9.8	1.6	3.1	3.1	23.5
RUS	1.3	1.3	1.3	4.9	0.9	0.9	0.9	3.4	6.7	6.7	6.7	24.4	19.2	19.2	19.2	70.5
SAF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
SAM	1.2	0.3	0.6	4.0	1.0	0.2	0.5	3.2	2.9	0.7	1.5	9.5	2.3	0.6	1.2	7.6
USA	0.5	1.0	0.5	1.3	0.5	0.9	0.5	1.2	9.3	18.6	9.3	24.8	0.8	1.6	0.8	2.1
WEU	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.2	1.6	1.6	0.2	0.0	0.2	0.2	0.0

	Storage Capacity (GtCO2) (Continued)															
	Low Cost Aquifers								High Cost Aquifers							
	Onshore				Offshore				Onshore				Offshore			
	Distance (km)				Distance (km)				Distance (km)				Distance (km)			
	100	500	1000	2000	100	500	1000	2000	100	500	1000	2000	100	500	1000	2000
AFR	4.7	14.1	9.4	65.8	4.7	14.1	9.4	65.8	5.6	16.7	11.1	77.7	5.6	16.7	11.1	77.7
AUS	10.5	7.0	17.5	35.0	94.5	63.0	157.5	315.0	0.6	0.4	1.0	2.0	5.4	3.6	9.0	18.0
BRA	21.7	21.7	39.0	4.3	195.1	195.1	351.1	39.0	28.3	28.3	51.0	5.7	254.9	254.9	458.9	51.0
CAM	0.2	2.0	0.4	1.8	2.0	17.8	4.0	15.8	0.3	2.3	0.5	2.1	2.3	21.0	4.7	18.7
CAN	13.2	26.4	79.1	145.1	4.4	8.8	26.4	48.4	35.6	71.1	213.4	391.1	11.9	23.7	71.1	130.4
CAS	7.5	1.5	16.5	4.5	2.5	0.5	5.5	1.5	8.9	1.8	19.6	5.3	3.0	0.6	6.5	1.8
CHN	40.2	160.7	401.6	200.8	13.4	53.6	133.9	66.9	13.7	54.6	136.5	68.3	4.6	18.2	45.5	22.8
EEU	0.4	0.6	0.6	0.3	3.3	5.8	5.0	2.5	1.0	1.8	1.5	0.8	9.2	16.0	13.7	6.9
IND	7.5	26.3	18.8	22.5	7.5	26.3	18.8	22.5	7.5	26.3	18.8	22.5	7.5	26.3	18.8	22.5
JAP	3.8	9.8	0.8	0.8	3.8	9.8	0.8	0.8	9.0	23.3	1.8	1.8	9.0	23.3	1.8	1.8
KOR	2.8	0.8	0.2	0.2	2.8	0.8	0.2	0.2	3.3	0.9	0.2	0.2	3.3	0.9	0.2	0.2
MEA	15.8	71.2	47.4	23.7	5.3	23.7	15.8	7.9	18.7	84.1	56.1	28.0	6.2	28.0	18.7	9.3
RAS	2.8	5.6	5.6	42.1	2.8	5.6	5.6	42.1	3.3	6.6	6.6	49.8	3.3	6.6	6.6	49.8
RUS	72.2	72.2	72.2	264.7	72.2	72.2	72.2	264.7	85.3	85.3	85.3	312.8	85.3	85.3	85.3	312.8
SAF	0.0	0.0	0.1	0.0	0.1	0.4	0.6	0.4	0.1	0.5	0.7	0.6	0.8	4.1	6.6	5.0
SAM	17.6	4.4	8.8	57.1	17.6	4.4	8.8	57.1	20.8	5.2	10.4	67.5	20.8	5.2	10.4	67.5
USA	63.9	127.9	63.9	170.5	21.3	42.6	21.3	56.8	172.3	344.6	172.3	459.5	57.4	114.9	57.4	153.2
WEU	3.2	28.9	28.9	3.2	1.1	9.6	9.6	1.1	8.8	79.4	79.4	8.8	2.9	26.5	26.5	2.9

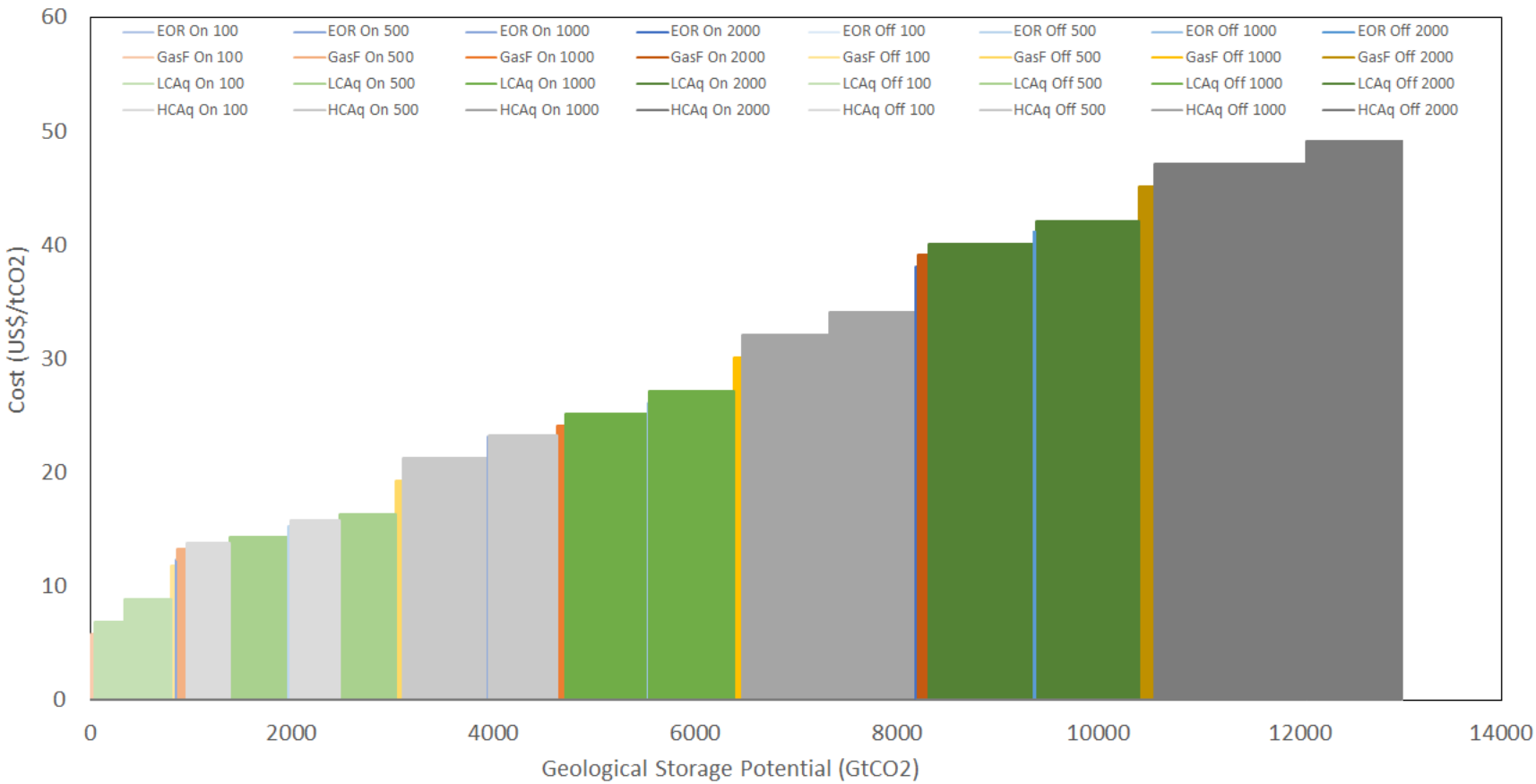


Figure 4-15 – Global supply curve for transportation and storage of CO_2.

Legend: EOR – Enhanced Oil Recovery; GasF – Gas Field; LCAq – Low Cost Aquifer; HCAq – High cost Aquifer;

On – Onshore; Off – Offshore;

Distance in km: 100, 500; 1000;2000.

5. Sectors and economic scenario

This chapter describes both the energy transformation sector (from primary to secondary and final energy) and the end-use sector. The later includes the Transportation, Industrial, Services (Commercial and Public Buildings), Agriculture and Household sectors. The last sector explored in this chapter is the Residues Treatment sector, which is relevant for GHG emissions, but not so much in terms of energy consumption.

Out of all the sectors previously mentioned, the energy sector is relatively different, since its activity is indirectly related to economic and population growth. In simple terms, the energy sector is responsive for the development of the end-use sectors and, therefore, endogenous.

That being said, determining the macroeconomic scenario is an important task in assessing future energy services demand from all sectors of an economy. The best approach to do is through a systemic and consistent model, such as a Computable General Equilibrium model, or CGE model.

CGE models have become a standard tool of empirical economic analysis. In recent years, improvements in model specification, data availability, and computer technology have improved the payoffs and reduced the costs of policy analysis based on CGE models, paving the way for their widespread use by policy analysts throughout the world (IFPRI, 2012).

This type of economic model are simulations that combine the abstract general equilibrium structure with realistic economic data to solve numerically for the levels of supply, demand and price that support equilibrium across a specified set of markets. CGE models are a standard tool of empirical analysis, and are widely used to analyse the aggregate welfare and distributional impacts of policies whose effects may be transmitted through multiple markets, or contain menus of different tax, subsidy, quota or transfer instruments (WING, 2004).

The fundamental conceptual starting point for a CGE model is the circular flow of commodities in a closed economy, shown in Figure 5-1.The main actors in the diagram are households, who own the production factor and are the final consumers of produced commodities, and firms, who rent the factors of production from the households for the purpose of producing goods and services that the households then consume. Many CGE models also explicitly represent the government, but their role in the circular flow is often

passive: to collect taxes and disburse these revenues to firms and households as subsidies and lump-sum transfers, subject to rules of budgetary balance that are specified by the analyst. In tracing the circular flow one can start with the supply of factor inputs (e.g. labour and capital services) to the firms and continue to the supply of goods and services from the firms to households, who in turn control the supply of factor services (WING, 2004).

Equilibrium in the economic flows in Figure 5-1 results in the conservation of both product and value. Conservation of product, which holds even when the economy is not in equilibrium, reflects the physical principle of material balance that the quantity of a factor with which households are endowed, or of a commodity that is produced by firms, must be completely absorbed by the firms or households (respectively) in the rest of the economy. Conservation of value reflects the accounting principle of budgetary balance that for each activity in the economy the value of expenditures must be balanced by the value of incomes, and that each unit of expenditure has to purchase some amount of some type of commodity (WING, 2004).

The implication is that neither product nor value can appear out of nowhere: each activity's production or endowment must be matched by others' uses, and each activity's income must be balanced by others' expenditures. Nor can product or value disappear: a transfer of purchasing power can only be effected through an opposing transfer of some positive amount of some produced good or primary factor service, and vice versa (WING, 2004).

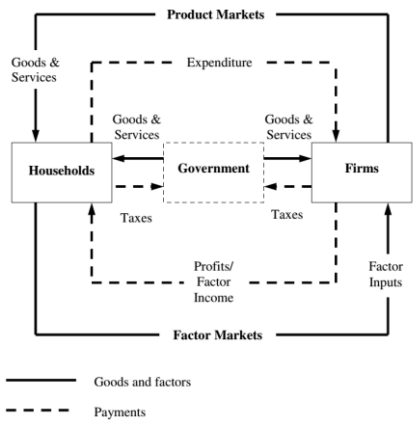


Figure 5-1 – Circular flow of the economy

Source: WING, 2004

Although computable general equilibrium (CGE) models are now used widely in policy analysis, their growing complexity has become an entry barrier for potential users, and the equation systems are becoming lengthy, hard to understand and difficult to modify or debug (WING, 2004).

The complexity is partly due to the lack of a clearly defined equation system that is used to solve the model. It is also the consequence of models being designed for multiple uses, with some variables and equations only required for some uses and many unnecessary for most uses (ZHANG, 2013).

CGE models have been used to analyse a wide range of policy issues, such as the economic implications of trade liberalisation, economic development and greenhouse gas abatement (ZHANG, 2013). To meet the growing demand for these types of analyses, more CGE models have been built and many existing models have been constantly updated and modified. As more features are added, the structure becomes increasingly complex and unwieldy, making it difficult to interpret results and adapt the models for new applications (ZHANG, 2013).

Despite being a complex tool, CGE models have been favoured in IAM frameworks to assure global consistency between all agents and sectors of the economy. The same tool can be used to estimate the demand of energy services and agriculture products. Depending on the modelling framework, this information can be used as input data for partial equilibrium models, such as the one developed in this study.

Despite the advantages of a CGE model to evaluate macroeconomic scenarios and potentially provide demands for energy services consistent with the socio-economic development, the development of such a model is beyond the scope of this work.

5.1.Macroeconomic scenario

As mentioned in the second chapter, the SSP scenarios were developed to support the integrated research community on mitigation of climate change and its impacts. The narratives explore a wide range of possible pathways within the context of climate change. In addition to different socioeconomic trajectories, each SSP correlates with different challenges to mitigation and/or adaptation.

This section addresses the macroeconomic scenario on which the global energy model developed in this thesis was build and tested. It is worth noting that the model itself

could be run on a number of different macroeconomic scenarios. However, one scenario was selected to make the first attempt of the model and to compare results with available literature.

Thus, amongst the various SSPs the SSP2 scenario was selected to be used in this study. The SSP2, as established in chapter 2, is a sort of "middle of the road" (O'NEIL, 2011) within the SSP framework. As such, it has intermediary challenges towards mitigation and adaptation.

According to the Boulder Report, in this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates (O'NEIL, 2011). Overall, historic trends are representative in the short to medium term.

Nevertheless, this scenario is arguably the scenario with less clear and precise premises, so that a countless number of scenarios could follow the general guideline. In fact, a sixth SSP scenario was discussed but dropped, due to being seen as a possible interpretation of the SSP2 scenario (O'NEIL, 2011).

5.1.1. Original SSP2 Data

The available data for SSP2 are mostly related to economic growth, in terms of Gross Domestic Product (GDP), and population growth. Very few additional socioeconomic information is available, such as urbanization, male/female distribution and age distribution. They are available for 190 countries.

The GDP growth rate for every region and decade are presented in Figure 5-2, whilst Figure 5-3 shows the global GDP until 2100. The historic data were taken from the World Bank database (WB, 2013). Overall, the regional GDP growth rates are declining, but only China reaches negative values in this scenario.

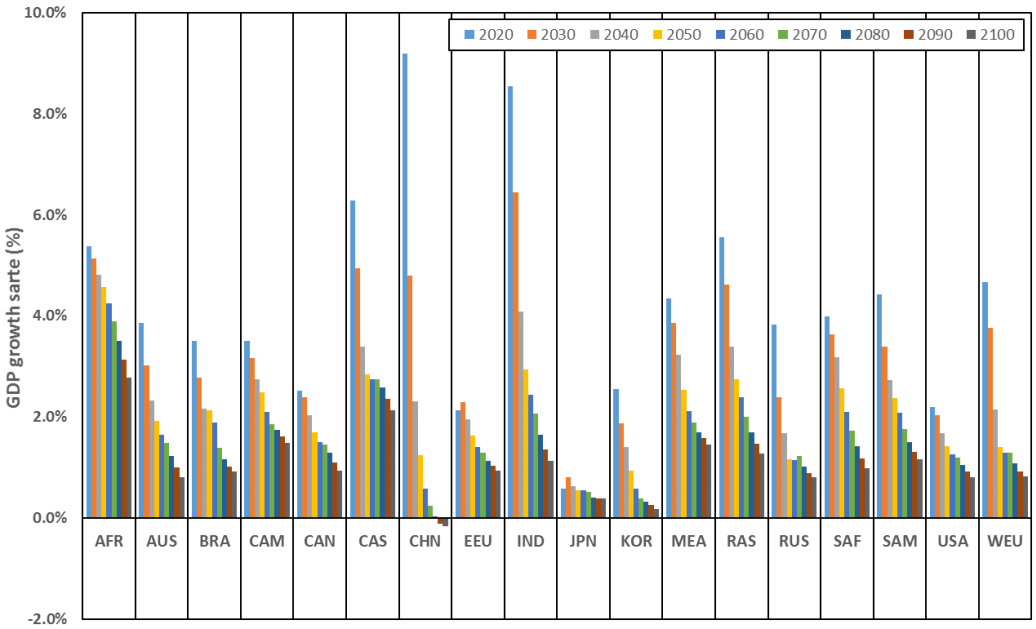


Figure 5-2 – Regional GDP 10-year growth rate

Source: Data adapted from IIASA, 2013a

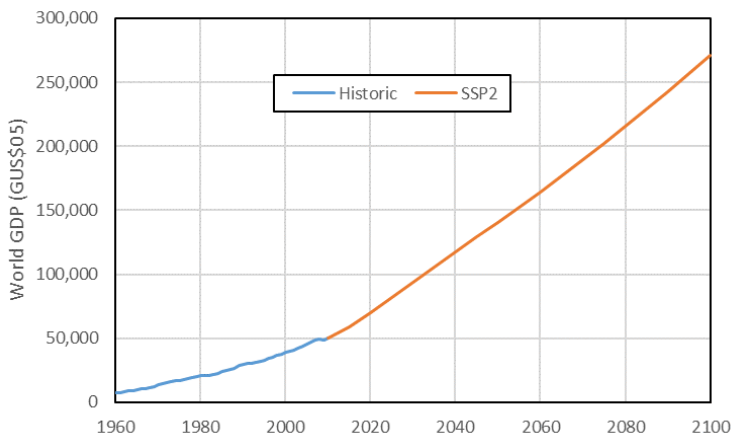


Figure 5-3 – World GDP (G US$05)

Source: Data adapted from WB, 2013 and IIASA, 2013a

Just as for GDP, Figure 5-4 and Figure 5-5 present the regional population growth rate and total global population, respectively. Interestingly, several regions present negative growth rate in the medium to long term. This results in the stagnation of the world population after the middle of the century, with a decline in population by the end of the century.

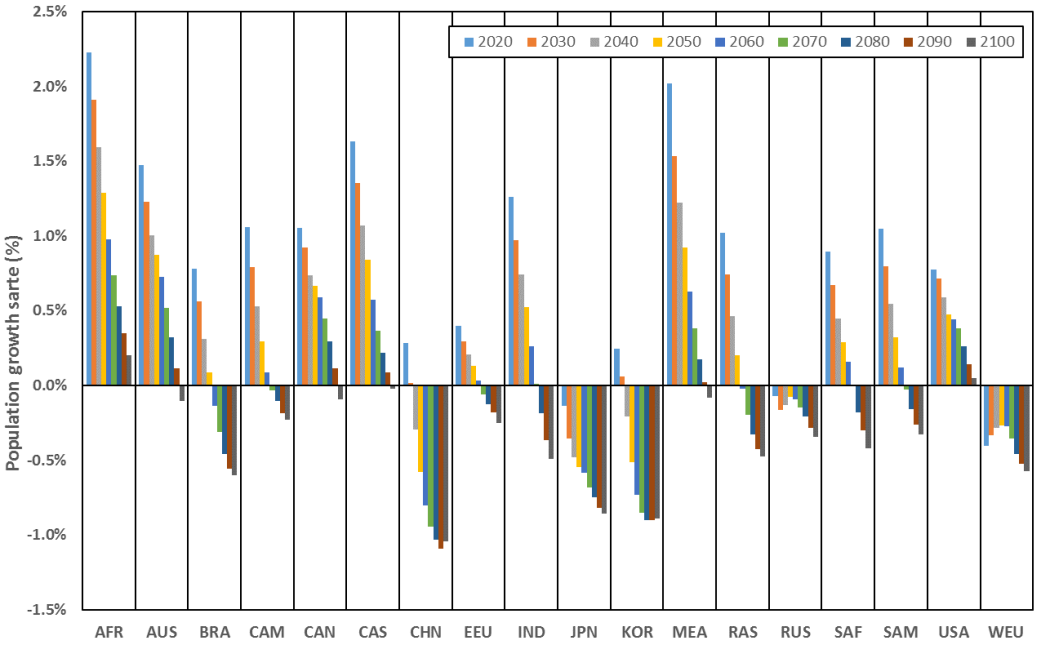


Figure 5-4 - Regional Population 10-year growth rate

Source: Data adapted from IIASA, 2013a

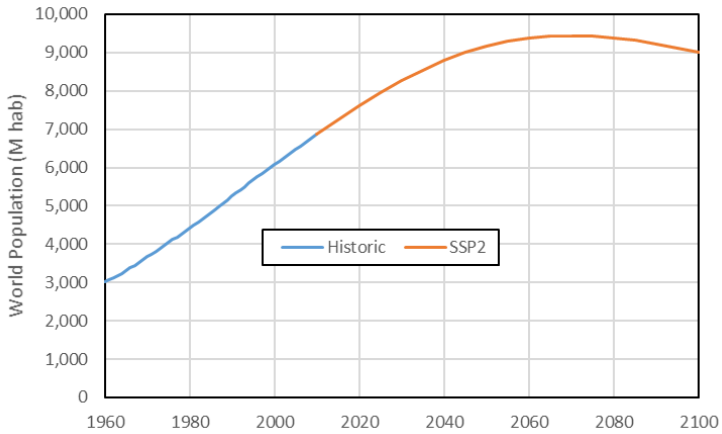


Figure 5-5 - World Population (G US$05)

Source: Data adapted from WB, 2013 and IIASA, 2013a

It is worth noting that Africa is the only region that shows both consistently high GDP growth rates and positive population growth rates thoughout the scenario. Also, China and India have relatively similar behaviour, with declining population growth rates and two-part behaviour regarding GDP growth rate: very high at first, but highly declining to the end of the century.

5.1.2. Economic interpretation of SSP2

As established before, the SSP2 database does not provide detailed information on socioeconomic development, such as sector composition or expenditure composition. This information could be useful to estimate energy services or products demand. In addition, as mentioned before, the tools for developing a macroeconomic consistent scenario are not within the scope of this study.

Nevertheless, this study has taken an approach to tackle this obstacle. Since the SSP2 interpretation is closely related to historical trends, they were used to determine the behaviour throughout the scenario. Thus, historical data for population, GDP, GDP composition (sector and expenditure) were taken from World Bank (2013) and the historical profile was determined.

For each region a profile for $(n-1)$ parts of the GDP composition were determined through the historical profile. For the sector composition, the Industry and Service sectors were assessed. For both, a historical growth rate was determined for each region, which was then applied forward.

In turn, they were used to estimate the future behaviour of the composition of the GDP. In Figure 5-7 and Figure 5-8 the historical and estimated future sector composition of GDP for every region are shown. Figure 5-6 summarises the global profile of sector GDP.

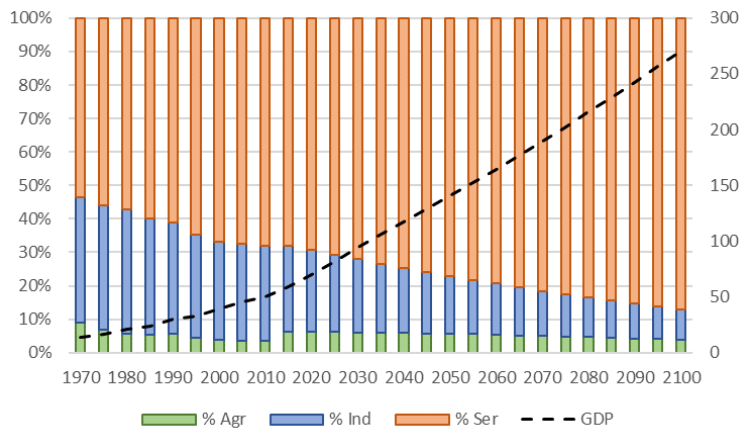


Figure 5-6 – Global GDP and GDP sector composition

Globally, there is a consistent decrease of Industry participation in GDP, followed by an increased importance of services sector, which includes both commercial and public

activities. This is in agreement with SSP2 interpretation that assumes that energy intensity decreases overtime (O'NEIL, 2011).

Once again, it is important to establish that these results are not necessarily consistent in macroeconomic terms, meaning that the balance between supply and demand of product and services between sectors of the economy is not being assessed in this study. This is a hindrance in developing a full IAM, which must be tackled in future works.

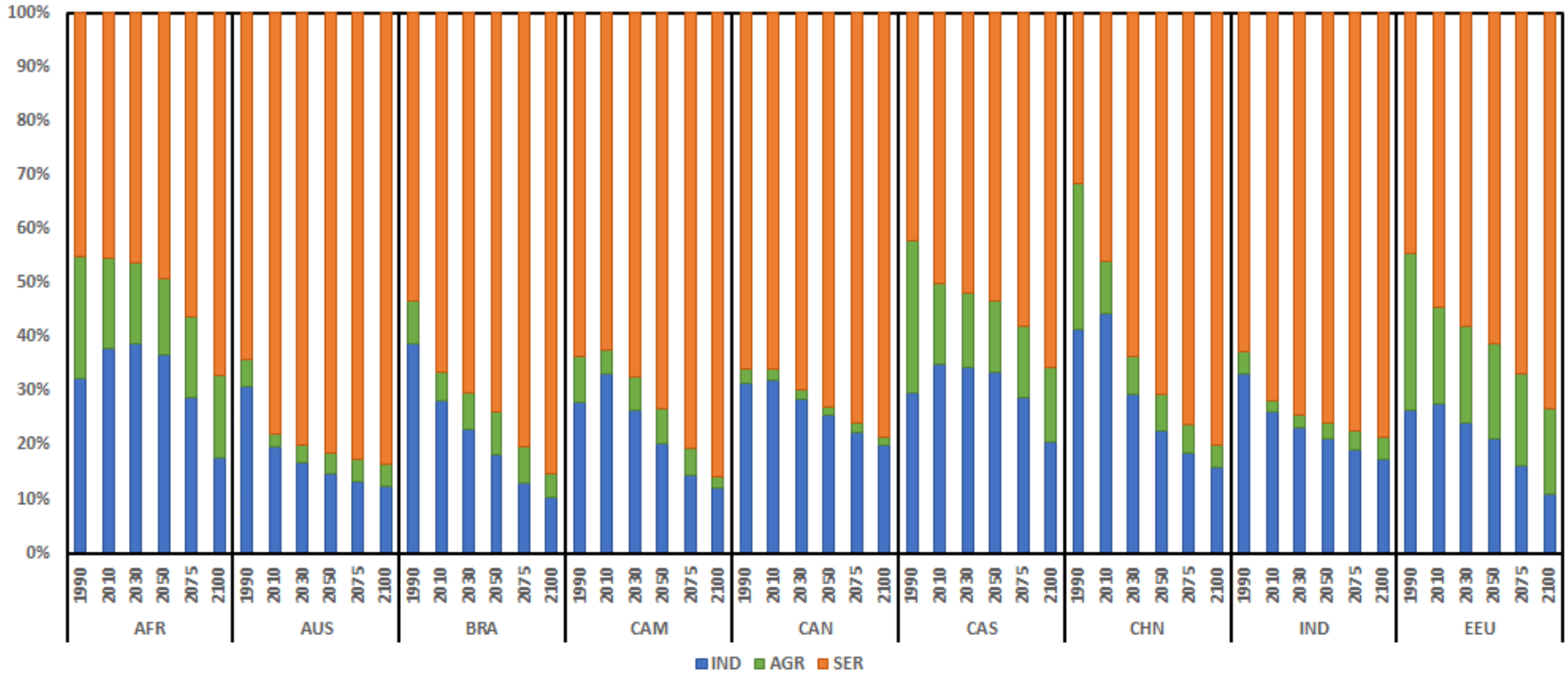


Figure 5-7 - GDP sector composition for every region (part 1)

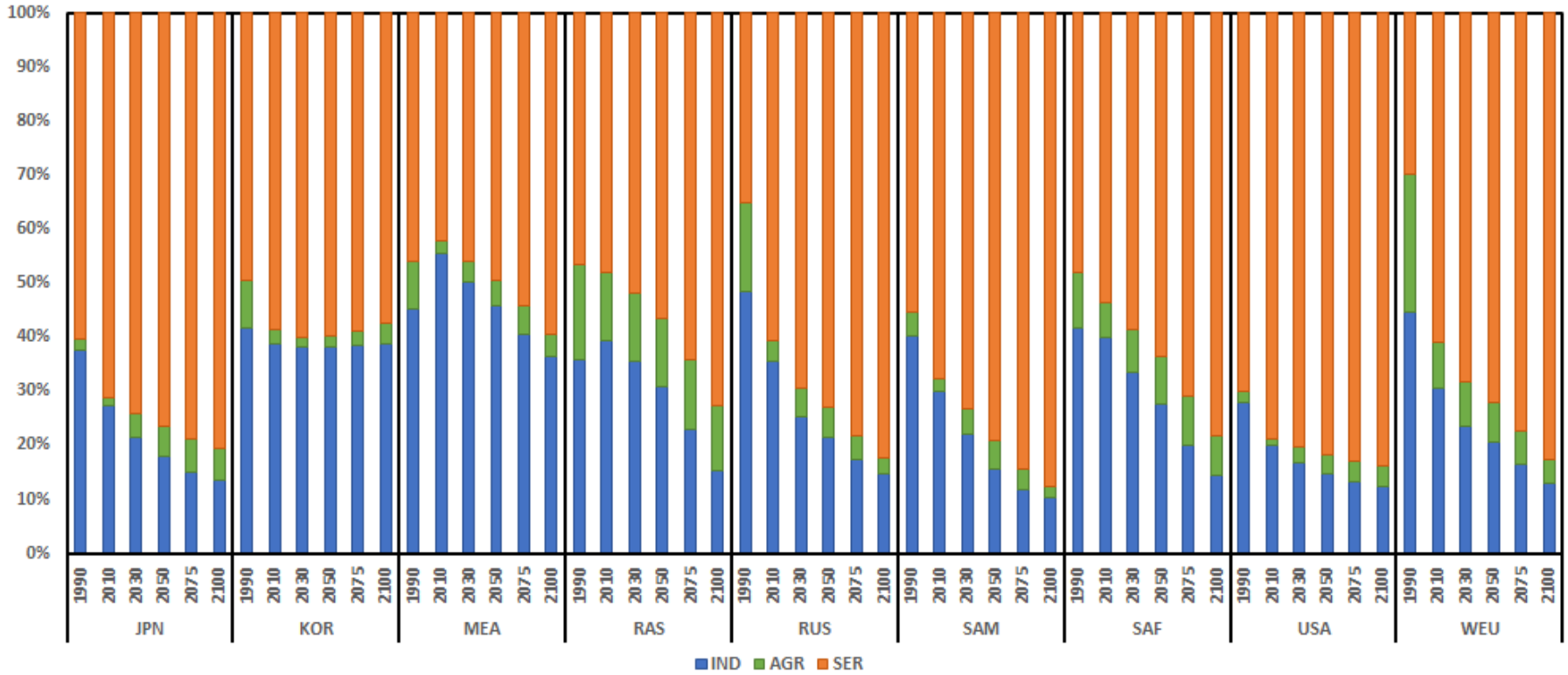


Figure 5-8 - GDP sector composition for every region (part 2)

Within this study, the GDP sector composition is used as the main driver for the energy service demand, as will be detailed in the following sections of this chapter. This includes Industry, Agriculture and Services (including Transportation) sectors.

However, sectors such as Households and Residues are directly related to population growth. However, population alone is not the only underlying factor involved. Consumption behaviour is also an important factor in determining energy service demand. This is a complex issue addressed in the literature (MARTISKAINEN, 2007; EHRHARDT-MARTINEZ, 2010; HEINEN, 2013; HANSSEN, 2014; ZHOU AND YANG, 2016) and is not the topic of this study.

This study took a simplified approach towards changes in energy consumption behaviour for households. The household expenditure (HHE) was used as a driver for consumption change in time. This is even more important in regions in which household expenditure is expected to increase in long term scenarios, such as Africa.

As such, the same procedure used to estimate sector composition of the GDP was used to assess expenditure composition. In this case, the historical profile was determined for Household Expenditure (HHE), Government Expenditure (GVE) and Capital Formation (CAP), leaving Trade Balance (BAL) as a free score to maintain the degree of freedom.

Expenditure composition presented very little changes in relative participation in GDP throughout the time period. This is clearly shown in Figure 5-9, which shows a small increase participation of HHE against GVE and CAP.

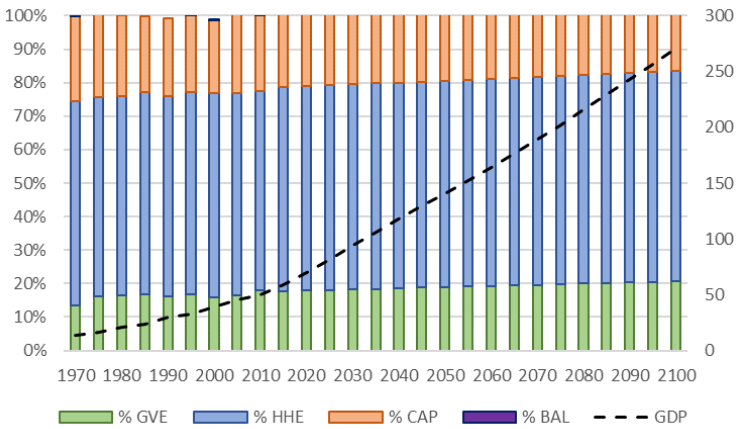


Figure 5-9 - Global GDP and GDP expenditure composition

Once again, it is worth noting that economic consistency is not assured within these results. For instance, estimated capital formation may not be consistent with GDP growth and sectorial composition. Nonetheless, the future composition is representative of the historical trend.

Thus, the economic interpretation of the SSP2 scenario developed in this section, even if methodologically limited, is used to determine energy service demand for every sector in the economy. The following sections of this chapter focus on such sectors.

5.2.Energy Sector

In the previous chapter, all primary energy sources were explored. However, resource extraction is only the first step of the Energy sector. The other part is related to the transformation of energy forms, i.e., from primary energy to secondary and, eventually, final energy. This study disaggregates these facilities into three main categories: Refining, Power and other fuels.

Overall, the energy sector is relatively different from other sectors included in this study due to its relationship with the macroeconomic scenario. Generally, the energy sector is reactive towards the energy demand of the other sectors of the economy, either within a region or from other regions. This is the opposite of other sectors, whose economic development is directly related to the energy demand.

5.2.1. Refining Sector

The first subsector of the Energy sector to be addressed is the Refining sector. It involves the processing of crude oils into several oil products, most of which are energy products, such as liquid fuels.

Oil processing is carried out in refineries, where crude oil is separated and converted into different fractions with the highest market value, such as gasoline, diesel, kerosene, etc. The configuration of a refinery depends on the characteristics of the crude oils and the range of products that the refinery offers to the market.

Oil refining is an energy-intensive industry, whose emissions of greenhouse gases are closely related to the consumption of fossil fuels. This consumption is related to the generation of direct heat, process steam and even electricity, all in stationary combustion

sources. The furnace processes and boilers account for about 56% of the emissions of a refinery (HPC, 2010), but these devices are in numerous sources scattered throughout the refinery, which can occupy a very large area.

Thus, oil processing demands a supply of energy, as splitting the crude oil into its refined products is not a spontaneous process. Usually, in a refinery, most of the energy consumption is granted by the oil itself, through its derivatives, such as fuel oil, coke and refinery gas.

Another important factor is that there is no standard refinery configuration. The structure of a refinery, and its complexity, is dependent on oil characteristics to be processed, the processing capacity, the production profile, specifications for the products and, finally, the choice of employed technologies. For this reason, it can be said that there are not two identical refineries in the world (SZKLO AND ULLER, 2008). In energy terms, self-consumption may vary between 4 and 15% of the refinery input (SZKLO AND SCHAFFER, 2007), depending on the refinery configuration.

DNV (2010) estimates that about 6% of global GHG emissions in 2005 had their origin in oil refineries. According to GHG emission inventories, oil refining is responsible for about 2.7%, 3.2% and 2.0% of total national emissions of the USA, European Union and Brazil, respectively (MCTI, 2013; PETROBRAS, 2013; EPA, 2014). Several studies in the literature have specific emissions in the order from 0.1 to 0.4 tCO_2/t of processed oil, with a closer average of 0.2 (CONCAWE, 2008; IEA-GHG, 2008; STRAELEN *et al.*, 2009; DNV, 2010).

In order to evaluate such a complex sector, a detailed methodology was used, not commonly used in global IAMs. The capacities of all process units were compiled by the OGJ (2011) database. The compiled data are available in Table 5-1. However, the capacity alone is not enough to estimate the production profile and energy requirements of refinery industries.

Table 5-1 – Refinery Unit Capacity per region (Mbbl/d)

Region	ACU	VCU	ASP	FCC	ALQ	CRU	TCU	HCC	DCU	HDT	LUB
AFR	2733	308	41	102	19	381	12	50	39	254	11
AUS	864	236	19	235	25	197	0	48	0	365	0
BRA	1908	810	27	505	6	24	10	0	115	240	20
CAM	2741	1325	86	469	139	359	144	45	259	383	29
CAN	1902	633	66	478	70	355	128	204	57	682	3
CAS	1502	456	22	111	2	178	76	20	110	224	31
CHN	8116	489	15	806	30	293	0	210	207	984	33
EEU	16435	6628	378	2510	271	2448	1668	1406	428	7037	173
IND	4000	812	38	503	85	52	93	166	170	178	8
JPN	4730	1764	84	987	75	829	20	182	123	3795	38
KOR	2722	477	44	212	29	266	0	306	19	889	46
MEA	7245	1982	97	358	38	660	539	597	90	1132	29
RAS	4157	1002	52	335	25	486	335	309	62	866	50
RUS	5431	2029	211	331	10	746	383	57	85	1384	83
SAF	487	201	8	108	10	78	61	12	27	118	8
SAM	2900	1227	53	577	73	172	168	67	250	460	21
USA	18442	8219	511	5858	1158	3670	71	1689	2529	275	202
WEU	1915	590	25	184	3	319	121	49	39	481	6

Fonte: Adapted data from OGJ, 2011

Legend: ACU – Atmospheric Distillation; VCU – Vacuum Distillation; ASP – Asphalt; FCC – Fluid Catalytic Cracking; ALQ – Alkylation; CRU – Catalytic Reforming; TCU – Thermal Cracking; HCC – Hydrocracking; DCU – Delayed Coking; HDT – Hydro treating; LUB - Lubricant

In order to assess and estimate these characteristics, a refining simulation tool called CAESER (Carbon and Energy Strategy Analysis for Refineries), described in GUEDES (2015) and GUEDES *et al.*(2016) was used. With this tool, the oil products production profile and the utilities consumption for each region were estimated, albeit in a simplified form.

The estimated data are available in Table 5-2, on which the total crude distillation capacity, production profile and utilities consumption are presented. The table presents estimated data for three type of runs: naphtha run, diesel run and kerosene run.

One major advantage of the approach used in this study, besides the detailing of energy products and consistent energy consumption associated, is that it allows estimating the CO_2 emissions related to process emissions, such as those associated with Hydrogen Generation Unit (HGU) and Fluid Catalytic Cracking (FCC) units.

Table 5-2 – Refinery output yield and utilities consumption estimated from CAESAR (%)

Parameter		AFR			AUS			BRA			CAM			CAN			CAS		
Type of Run		Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene
Output (%)	RefGas	0.9	0.9	0.9	1.9	1.8	1.7	1.9	1.9	1.9	2.1	2.1	2.1	1.7	1.7	1.6	1.4	1.4	1.4
	LPG	1.4	1.2	1.4	3.8	3.7	3.7	5.4	5.2	5.4	3.7	3.7	3.7	3.0	2.9	2.9	2.5	2.3	2.5
	Naphtha	18.7	16.9	14.8	26.2	24.3	23.0	30.9	29.1	27.0	26.6	24.4	22.7	25.1	22.9	21.6	20.3	18.5	16.4
	Gasoil	44.0	48.5	48.5	50.9	55.4	52.8	42.8	47.3	47.3	43.9	48.4	48.4	54.5	59.0	59.0	43.5	48.0	48.0
	Coke	0.5	0.5	0.5	0.7	0.7	0.7	2.5	2.5	2.5	3.0	3.0	3.0	1.2	1.2	1.2	2.1	2.1	2.1
	Heavy	30.6	30.6	30.6	16.1	16.1	16.1	25.6	25.6	25.6	36.1	36.1	36.1	14.3	14.3	14.3	26.3	26.3	26.3
Utilities (%)	H2	1.3	1.3	1.4	4.9	4.9	5.1	0.6	0.6	0.7	1.3	1.3	1.5	6.7	6.7	7.1	1.1	1.1	1.5
	Steam	0.5	0.5	0.5	0.6	0.6	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.7	0.7	0.7	0.4	0.4	0.4
	Heat	4.3	4.3	4.3	6.7	6.4	6.3	4.6	4.6	4.7	5.7	5.7	5.8	6.4	6.4	6.3	4.8	4.8	5.0
	FCC Coke	0.2	0.2	0.2	1.2	1.2	1.2	1.7	1.7	1.7	1.1	1.1	1.1	0.8	0.8	0.8	0.5	0.5	0.5
	Elect	0.2	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.2	0.2	0.2
Parameter		CHN			EEU			IND			JPN			KOR			MEA		
Type of Run		Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene
Output (%)	RefGas	0.9	0.9	0.9	1.7	1.7	1.7	1.1	1.1	1.1	2.1	2.1	2.0	0.9	0.9	0.9	0.8	0.8	0.8
	LPG	2.5	2.3	2.5	3.3	3.3	3.3	2.6	2.6	2.6	4.2	4.2	4.2	2.1	1.9	2.1	1.8	1.6	1.8
	Naphtha	23.0	21.2	19.1	26.5	24.3	22.6	26.3	24.1	22.5	27.7	25.4	24.1	23.9	21.9	20.0	21.2	19.4	17.3
	Gasoil	46.8	51.2	51.2	55.0	59.5	59.5	45.1	49.5	49.6	50.5	58.6	54.1	53.6	58.1	58.1	50.0	54.5	54.5
	Coke	0.9	0.9	0.9	1.2	1.2	1.2	1.5	1.5	1.5	1.5	1.5	1.5	0.5	0.5	0.5	0.5	0.5	0.5
	Heavy	22.2	22.2	22.2	21.2	21.2	21.2	21.2	21.2	21.2	16.1	16.1	16.1	17.7	17.7	17.7	22.6	22.6	22.6
Utilities (%)	H2	2.2	2.2	2.4	6.3	6.3	6.7	2.1	2.1	2.1	6.6	6.6	7.6	6.7	6.7	7.4	4.8	4.8	5.0
	Steam	0.6	0.6	0.6	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.8	0.6	0.6	0.7
	Heat	3.7	3.7	3.8	6.3	6.3	6.5	3.6	3.6	3.7	7.4	7.4	7.8	4.9	4.9	5.2	4.2	4.2	4.4
	FCC Coke	0.6	0.6	0.6	1.0	1.0	1.0	0.8	0.8	0.8	1.3	1.3	1.3	0.5	0.5	0.5	0.3	0.3	0.3
	Elect	0.2	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.2	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.2
Parameter		RAS			RUS			SAF			SAM			USA			WEU		
Type of Run		Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene
Output (%)	RefGas	1.1	1.1	1.1	1.0	1.0	1.0	2.2	2.2	2.2	1.9	1.9	1.9	2.9	2.9	2.8	1.4	1.4	1.3
	LPG	2.3	2.1	2.3	2.1	1.9	2.1	4.5	4.4	4.5	4.0	4.0	4.0	5.0	4.9	4.9	2.8	2.6	2.8
	Naphtha	22.3	20.5	18.4	19.0	17.2	15.1	28.4	26.2	24.6	29.1	26.8	25.2	30.0	28.1	26.8	20.6	18.8	16.8
	Gasoil	50.9	55.3	55.3	43.0	47.5	47.5	45.3	49.8	49.8	45.8	50.3	50.3	48.8	53.2	53.3	44.6	49.1	49.1
	Coke	0.7	0.7	0.7	0.6	0.6	0.6	2.2	2.2	2.2	2.9	2.9	2.9	4.2	4.2	4.2	0.9	0.9	0.9
	Heavy	20.2	20.2	20.2	36.5	36.5	36.5	26.3	26.3	26.3	25.8	25.8	25.8	19.4	19.4	19.4	25.7	25.7	25.7
Utilities (%)	H2	4.6	4.6	4.8	0.8	0.8	1.9	2.1	2.1	2.5	2.0	2.0	2.0	4.2	4.2	4.3	1.7	1.7	2.6
	Steam	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5
	Heat	4.8	4.8	4.9	4.4	4.4	4.9	6.2	6.2	6.4	5.2	5.2	5.2	7.1	7.0	6.7	5.0	5.0	5.4
	FCC Coke	0.5	0.5	0.5	0.4	0.4	0.4	1.4	1.4	1.4	1.3	1.3	1.3	1.4	1.4	1.4	0.6	0.6	0.6
	Elect	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.2	0.2	0.3

The estimated data so far are all related to existing refineries. For future expansions, the approach was to provide two refinery configurations: a high naphtha yield greenfield refinery and a high diesel yield greenfield refinery. The proposed refinery schemes (presented in Figure 5-10) were optimized in CAESER to provide the highest yield possible for the desired main product.

The objective is to give the model flexibility in terms of refinery expansion, depending on the demand of oil products in the future. The estimated data for both refinery options are shown in Table 5-3.

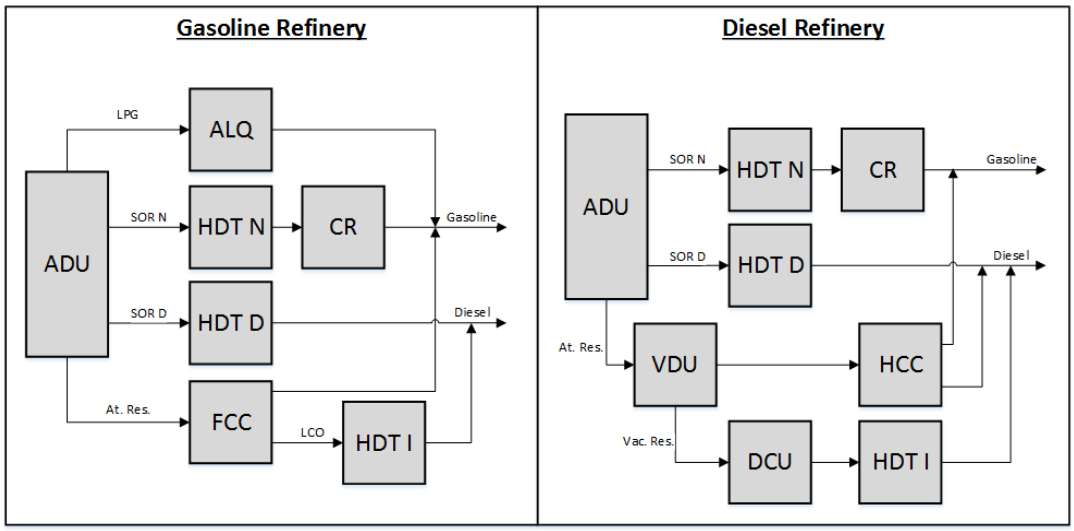


Figure 5-10 – Simplified refinery schemes for gasoline (left) and diesel (right)

Table 5-3 -New refinery output yield and utilities consumption estimated from CAESAR

Parameter		New Gasoline			New Diesel		
Type of Run		Naphtha	Diesel	Kerosene	Naphtha	Diesel	Kerosene
Output (%)	RefGas	1.9	1.9	1.9	1.6	1.6	1.5
	LPG	5.8	5.8	5.8	2.1	1.9	2.1
	Naphtha	34.9	32.7	31.1	20.8	19.1	17.3
	Gasoil	47.7	52.2	52.2	64.4	68.9	68.9
	Coke	1.3	1.3	1.3	3.0	3.0	3.0
	Heavy	4.9	4.9	4.9	3.9	3.9	3.9
Utilities (%)	H2	2.4	2.4	2.4	3.9	4.2	5.1
	Steam	0.7	0.7	0.7	0.6	0.6	0.7
	Heat	5.0	5.0	5.0	6.4	6.3	6.1
	FCC Coke	2.1	2.1	2.1	0.0	0.0	0.0
	Elect	0.3	0.3	0.3	0.4	0.4	0.4

5.2.2. Power Sector

The electricity sector is another complex subsector within the Energy sector also assessed in this study. In this section, all the transformation of primary energy and secondary energy sources into electricity within the model is presented. The main input energy sources and technologies are presented in Figure 5-11.

Firstly, it is worth noting that coal technologies are split into three fuel categories (Bituminous, Subbituminous and Lignite), just as the coal resources, described in Chapter 4. Regarding the technologies, there are up to seven technologies per fuel: Subcritical Rankine, Supercritical Rankine, Ultra-supercritical Rankine, Integrated Gasification Combined Cycle (IGCC), and all previous technologies with carbon capture.

The subcritical system is the conventional technology. Its steam cycle operates at steam pressures below 22 MPa and temperatures can reach approximately 550° C. The efficiency of these generating units is in a range of 33% to 37% (HHV) (MIT, 2007). The generation efficiency can be increased considerably when designing steam cycle equipment for operation at higher pressures and temperatures, which lead to supercritical conditions in the steam cycle, causing the increase in enthalpy change in the turbine, consequently generating more work. In supercritical plants, generation efficiencies are in the range of 37% to 40% (HHV). Plants at the state of the art operate at pressures of about 24.3 MPa and 565° C in steam cycle (MIT, 2007).

From the development of new materials, pressure ranges and operating temperature can be expanded. The electricity sector, especially in Europe and Japan, takes advantage of this development to operate the steam cycle in more severe conditions than the typical supercritical, above 565° C. This technology is referred to in the literature as "ultra-supercritical". Several plants, which operate with pressures up to 32 MPa and temperatures up to 600/610 ° C, have recently been installed in Europe and Japan. In this configuration, efficiency can reach the range of 44 to 46% (HHV) (MIT, 2007).

As for natural gas technologies, this thesis considered three technologies: Brayton Cycle, Combined Cycle and Subcritical Rankine. The first, also known as Open Cycle, is based on gas combustion turbines, most commonly used for peak loading. The second on the list, known as NGCC, is a combination between the Brayton Cycle and Rankine Cycle. It presents a higher efficiency than Open Cycle. The final option is a typical Rankine cycle ran on Natural Gas, which is an older technology.

For liquid fuels, two main technologies were considered: internal combustion engines and another version of the Rankine cycle. Regarding solid biomass, the two main technologies considered were, again, Rankine cycle and another version of IGCC. For both technologies, carbon capture was considered. Nuclear power technologies are also considered, with high technological breakdown, and are presented in more detail in the next section.

As for other renewables, such as Solar, Wind and Hydro, the technology breakdown follows the profile of the resources, already presented in the previous chapter. Again, the breakdown can be seen in Figure 5-11[5].

Ultimately, for all the presented power technologies, an estimation of the current installed capacity in all regions was performed. The main source of information towards creating this database was the Global Energy Observatory (GEO, 2016). The findings are presented in Table 5-4. The only exception, in Table 5-5, is nuclear power plants, for which the International Atomic Energy Agency database is more detailed (IAEA, 2015a).

In order to compare the compiled data based on GEO (2016), the database was compared to IEA (2015). The weakness in the IEA (2015) data is the technology breakdown. Thus, the installed capacity for every region is compared in Figure 5-12. Meanwhile, Figure 5-13 presents the comparison based on the aggregated energy source.

For both cases, minor differences can be seen. Region-wise, the larger difference comes in China (CHN) and East Europe (EEU), where GEO data are slightly lower than WEO data. As for energy sources, there appears to be an exchange between natural gas and oil capacity that cancel each other. The major difference in this estimate are related to hydro and wind energy. Either way, overall the estimated database is in accordance with the available literature.

[5] For economic details of energy technologies, see Annex 1.

Betuminous	PP_BetCoal_IGCC
	PP_BetCoal_USC
	PP_BetCoal_SC
	PP_BetCoal_SubC
	PP_BetCoal_IGCC_CCS
	PP_BetCoal_USC_CCS
	PP_BetCoal_SC_CCS
Sub-betuminous	PP_BetCoal_SubC_CCS
	PP_SubbetCoal_USC
	PP_SubbetCoal_SC
	PP_SubbetCoal_SubC
	PP_SubbetCoal_USC_CCS
	PP_SubbetCoal_SC_CCS
	PP_SubbetCoal_SubC_CCS
Lignite	PP_LigCoal_SC
	PP_LigCoal_SubC
Natural Gas	PP_NG_GT
	PP_NG_NGCC
	PP_NG_NGCC_CCS
	PP_NG_SubC
Fuel Oil	PP_FO_SubC
	PP_FO_Engine
Diesel	PP_Diesel_SubC
	PP_Diesel_Engine
Pet. Coke	PP_Petcoke_IGCC
	PP_Petcoke_SubC
Biomass	PP_Bio_SubC
	PP_Bio_SubC_CCS
	PP_Bio_IGCC
	PP_Bio_IGCC_CCS
Nuclear	PP_Nuclear_PWR
	PP_Nuclear_BWR
	PP_Nuclear_APWR
	PP_Nuclear_GCR
	PP_Nuclear_PHWR
	PP_Nuclear_LWGR
	PP_Nuclear_FBR
	PP_Nuclear_HTGR
Solar	PP_Solar_PV
	PP_Solar_CSP
	PP_Solar_CSP_7h
	PP_Solar_CSP_12h

Hydro	PP_Hydro_Large_Existing
	PP_Hydro_Large_Categ1
	PP_Hydro_Large_Categ2
	PP_Hydro_Large_Categ3
	PP_Hydro_Large_Categ4
	PP_Hydro_Large_Categ5
	PP_Hydro_Small_Categ1
	PP_Hydro_Small_Categ2
	PP_Hydro_Small_Categ3
	PP_Hydro_Small_Categ4
	PP_Hydro_Small_Categ5
Wind Onshore	PP_WindOn_100km_C1
	PP_WindOn_100km_C2
	PP_WindOn_100km_C3
	PP_WindOn_100km_C4
	PP_WindOn_200km_C1
	PP_WindOn_200km_C2
	PP_WindOn_200km_C3
	PP_WindOn_200km_C4
	PP_WindOn_1500km_C1
	PP_WindOn_1500km_C2
	PP_WindOn_1500km_C3
	PP_WindOn_1500km_C4
Wind Offshore	PP_WindOff_100km_C1_shallow
	PP_WindOff_100km_C1_transitional
	PP_WindOff_100km_C1_deep
	PP_WindOff_100km_C2_shallow
	PP_WindOff_100km_C2_transitional
	PP_WindOff_100km_C2_deep
	PP_WindOff_100km_C3_shallow
	PP_WindOff_100km_C3_transitional
	PP_WindOff_100km_C3_deep
	PP_WindOff_200km_C1_shallow
	PP_WindOff_200km_C1_transitional
	PP_WindOff_200km_C1_deep
	PP_WindOff_200km_C2_shallow
	PP_WindOff_200km_C2_transitional
	PP_WindOff_200km_C2_deep
	PP_WindOff_200km_C3_shallow
	PP_WindOff_200km_C3_transitional
	PP_WindOff_200km_C3_deep
	PP_WindOff_1500km_C1_shallow
	PP_WindOff_1500km_C1_transitional
	PP_WindOff_1500km_C1_deep
	PP_WindOff_1500km_C2_shallow
	PP_WindOff_1500km_C2_transitional
	PP_WindOff_1500km_C2_deep
	PP_WindOff_1500km_C3_shallow
	PP_WindOff_1500km_C3_transitional
	PP_WindOff_1500km_C3_deep

Figure 5-11 – Power Technologies and energy sources

Table 5-4 – Installed capacity of power technology and region (GW)

		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Betuminous Coal	Sub-critical ST	8.0	25.1	4.9	4.9	27.1	17.8	50.3	134.1	260.4	6.3	28.0	4.8	45.5	10.4	46.6	7.1	246.1	24.6
Betuminous Coal	Super-critical ST	0.0	1.6	0.0	0.0	0.0	0.0	78.2	10.9	22.1	31.2	0.0	0.0	7.7	0.0	0.0	0.0	0.6	0.0
Betuminous Coal	Super-critical ST 2	0.0	1.7	0.0	0.0	0.0	0.0	73.0	6.2	18.5	4.8	0.0	0.0	0.0	1.3	0.0	0.0	5.1	0.0
Betuminous Coal	CHP Steam Turbine	0.0	0.0	0.0	0.0	0.0	0.0	3.9	16.5	0.0	0.0	0.0	0.0	0.6	21.1	0.0	0.0	0.2	1.8
Coal Syngas	IGCC	0.0	0.9	0.0	0.0	0.0	0.0	0.7	4.1	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.0	4.2	0.0
Sub-bituminous Coal	Sub-critical ST	0.0	2.5	0.0	0.0	7.2	0.0	0.0	8.3	5.1	0.0	0.0	0.0	24.8	2.2	0.0	1.2	148.7	1.4
Sub-bituminous Coal	Super-critical ST	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	2.3	0.0	0.0	0.0	0.0	2.7
Sub-bituminous Coal	Super-critical ST 2	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0
Sub-bituminous Coal	CHP Steam Turbine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.1	0.0
Lignite	Sub-critical ST	0.0	8.2	0.0	0.0	1.9	0.0	1.0	77.4	12.3	0.0	0.0	0.0	7.4	3.1	0.0	0.0	19.7	7.7
Lignite	Super-critical ST	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
Lignite	CHP Steam Turbine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1	0.0	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0	0.0
Diesel	Sub-critical ST	0.0	0.8	0.1	0.1	1.2	0.0	0.0	2.5	0.0	18.4	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.4
Diesel	Oil Engine	0.2	0.2	0.4	0.2	2.7	0.0	0.3	1.6	4.4	4.1	0.3	11.3	0.8	0.0	0.0	0.0	27.0	0.0
Diesel	CHP Steam Turbine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuel Oil	Sub-critical ST	8.2	0.2	2.1	0.5	8.0	9.3	0.0	18.6	0.0	26.0	3.4	21.3	3.0	0.0	0.0	1.2	0.9	0.9
Fuel Oil	Oil Engine	5.7	0.2	0.2	14.9	1.1	3.4	0.0	6.0	1.2	16.0	1.3	18.7	4.2	0.0	0.0	0.1	51.3	0.0
Fuel Oil	CHP Steam Turbine	0.0	0.0	0.2	0.0	0.0	0.1	0.0	1.4	0.0	0.0	0.0	3.8	0.0	0.9	0.0	0.0	0.0	0.2
Petroleum Coke	Sub-critical ST	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0
Petroleum Coke	Gasification	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.4	0.0	0.0	0.2	0.0	0.0	0.0	3.5	0.0
Natural Gas	OCGT	21.1	11.7	1.9	0.6	7.3	2.0	1.4	12.9	2.3	0.8	1.5	31.2	8.5	4.0	3.5	10.2	110.0	0.1
Natural Gas	CCGT	49.8	3.5	9.0	22.5	13.9	9.6	34.7	211.9	49.0	77.8	31.8	87.8	92.0	5.1	0.0	25.6	324.1	0.7
Natural Gas	Sub-critical ST	20.9	1.8	0.0	0.0	0.3	15.5	0.0	12.2	0.0	15.8	0.5	2.3	9.6	10.1	0.0	8.3	0.7	4.2
Natural Gas	CHP Gas Turbine	0.0	0.6	0.3	0.0	1.1	0.0	0.0	0.7	0.2	0.8	0.0	2.9	0.7	0.0	0.0	2.7	0.0	0.0
Natural Gas	CHP CCGT	0.0	0.1	2.2	0.0	3.8	0.0	1.2	21.0	0.2	22.2	1.0	12.9	2.7	13.6	0.0	0.0	2.9	1.3
Natural Gas	CHP Steam Turbine	0.0	0.0	0.0	0.0	1.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	51.3	0.0	0.0	0.0	4.6
Biomass	Sub-critical ST	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0
Biomass	CHP Steam Turbine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Biomass	Gasification	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bagasse	Sub-critical ST	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bagasse	CHP Steam Turbine	0.0	0.0	6.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BioGas	OCGT	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0
Black Liquor	Sub-critical ST	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0
Nuclear	All Tech.	0.0	0.0	2.0	1.4	45.6	1.8	35.7	146.9	9.1	24.5	21.3	1.0	0.0	10.0	3.8	1.4	3.2	27.7
Hydro	All Tech.	31.5	17.8	84.0	14.6	98.5	28.4	48.3	140.1	77.7	32.4	7.6	18.0	30.0	91.9	2.6	51.7	155.3	17.0
Wind	All Tech.	1.6	2.7	0.9	0.4	3.2	0.0	0.0	8.3	0.5	0.0	0.3	0.0	0.2	0.0	0.0	0.4	10.1	0.0
Geothermal	All Tech.	0.2	0.8	0.0	2.2	0.0	0.0	0.0	5.2	0.0	1.0	0.0	0.0	3.2	0.0	0.0	0.0	2.8	0.0
Solar	All Tech.	0.1	0.0	0.0	0.0	0.2	0.0	0.0	3.0	0.2	0.0	0.0	0.2	0.0	0.0	0.1	0.0	4.1	0.0

Source: Adapted from GEO (2016)

Table 5-5 – Installed capacity and expected expansion of Nuclear reactors (MW)

MW	PWR		BWR		GCR		PHWR		LWGR		FBR		HTGR		Total	
	2015	2020	2015	2020	2015	2020	2015	2020	2015	2020	2015	2020	2015	2020	2015	2020
AFR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BRA	1,884	3,129	0	0	0	0	0	0	0	0	0	0	0	0	1,884	3,129
CAM	0	0	1,330	1,330	0	0	0	0	0	0	0	0	0	0	1,330	1,330
CAN	0	0	0	0	0	0	13,500	13,500	0	0	0	0	0	0	13,500	13,500
CAS	975	1,605	0	0	0	0	90	90	0	0	0	0	0	0	1,065	1,695
CHN	17,687	43,243	0	0	0	0	1,300	1,300	0	0	20	20	0	200	19,007	44,763
EEU	102,056	106,166	13,652	13,652	8,175	8,175	1,300	1,300	0	0	0	0	0	0	125,183	129,293
IND	917	1,834	300	300	0	0	4,091	6,611	0	0	0	470	0	0	5,308	9,215
JPN	19,284	19,284	23,104	25,754	0	0	0	0	0	0	0	0	0	0	42,388	45,038
KOR	18,076	24,446	0	0	0	0	2,641	2,641	0	0	0	0	0	0	20,717	27,087
MEA	915	4,950	0	0	0	0	0	0	0	0	0	0	0	0	915	4,950
RAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RUS	13,875	20,457	0	0	0	0	0	0	10,219	10,219	560	1,349	0	0	24,654	32,025
SAF	1,860	1,860	0	0	0	0	0	0	0	0	0	0	0	0	1,860	1,860
SAM	0	25	0	0	0	0	1,627	1,627	0	0	0	0	0	0	1,627	1,652
USA	64,741	70,374	33,898	33,898	0	0	0	0	0	0	0	0	0	0	98,639	104,272
WEU	13,107	17,225	0	0	0	0	0	0	0	0	0	0	0	0	13,107	17,225

Source: Adapted from IAEA, 2015a

Legend: PWR – Pressurized Water Reactor, BWR – Boiling Water Reactor, GCR – Gas-Cooled Reactor, PHWR – Pressurized Heavy Water Reactor, LWGR – Light Water Graphite Reactor, FBR – Fast Breeder Reactor, HTGR – High Temperature Gas Reactor

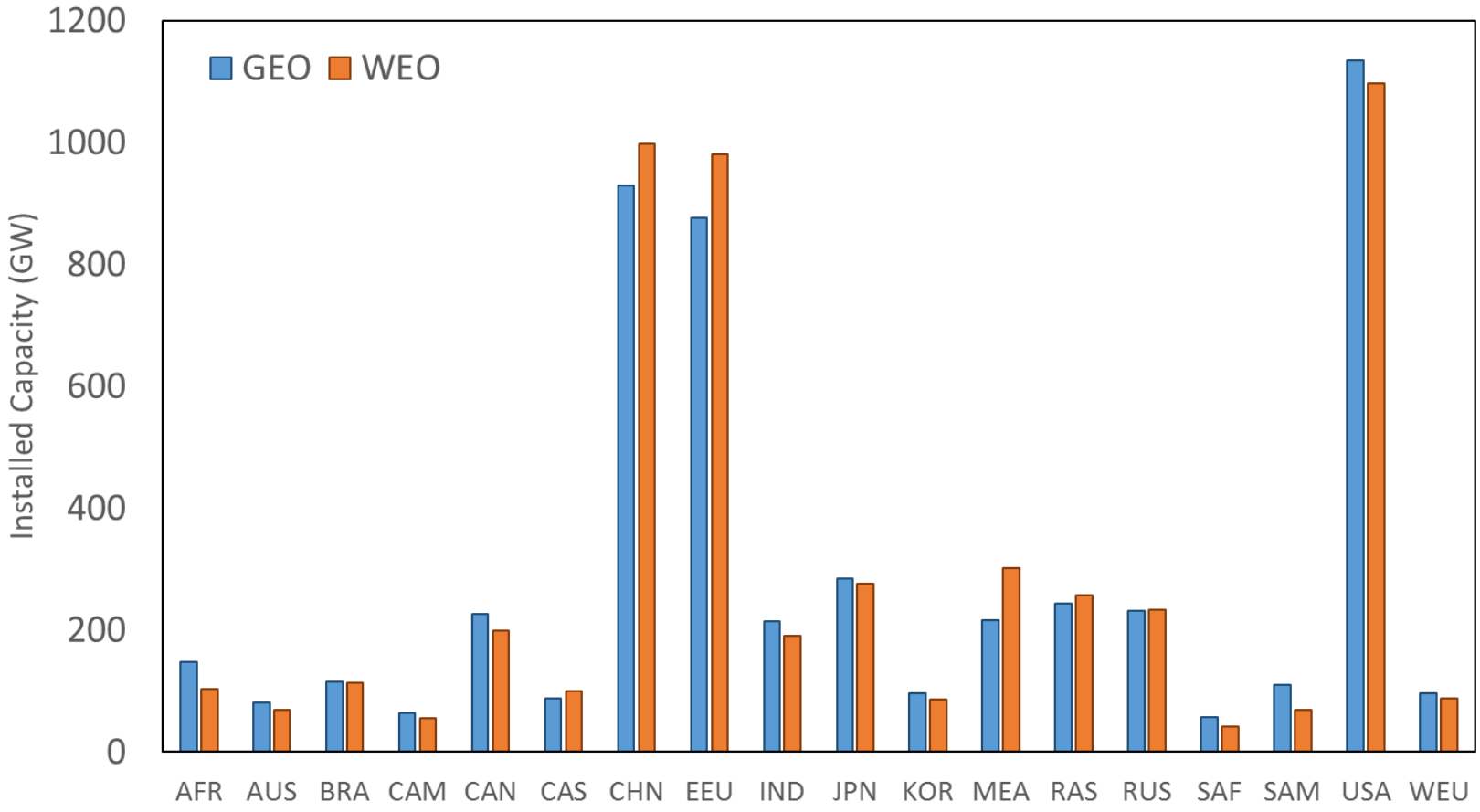


Figure 5-12 - Comparing installed capacity by region in 2013

Source: GEO (2016) and IEA (2015)

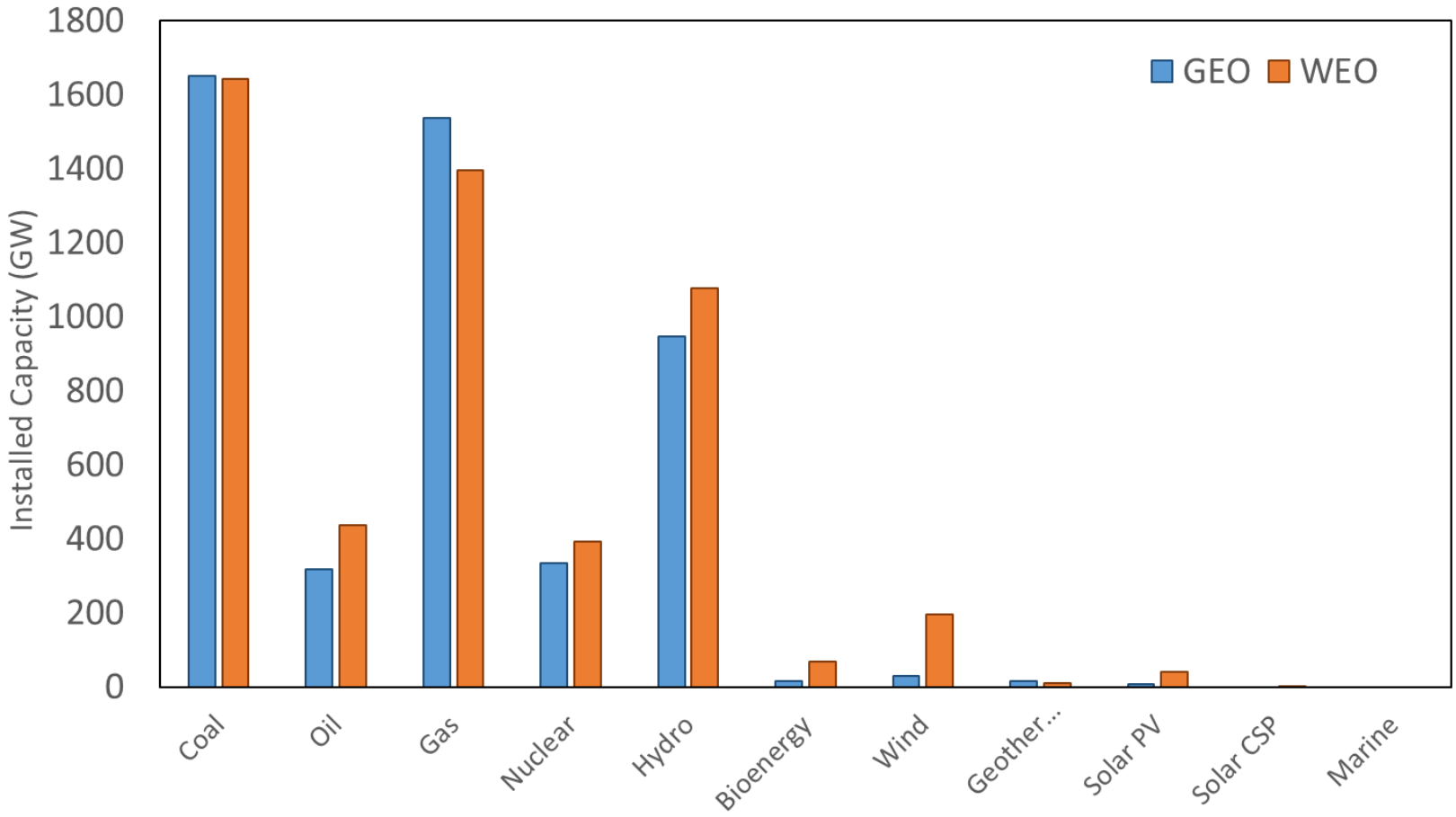


Figure 5-13 – Comparing installed capacity by energy source in 2013

Source: GEO (2016) and IEA (2015)

5.2.3. Other Fuels

This section is related to energy sources that are not addressed in the previous sections. It includes either solid, liquid of gaseous fuels that fail to fit into the oil refinery and power technology categories.

Regarding solid fuels, besides three categories of coal and solid biomass, the main solid fuel option available in the model are nuclear fuels. The model developed in this study takes a relative detailed approach for nuclear power technologies, differentiating reactor technology and, consequently, nuclear fuels. Thus, the type of nuclear fuel is depended on the nuclear reactor used.

Table 5-6 presents all nuclear fuels options available in the model. The main difference in uranium-based fuels is related to the enrichment. The level of enrichment is indirectly related to the burn-up, which is a measure of the amount of energy released by mass of fuel used. Typically, the unit is in GWd/t, or similar unit.

Table 5-6 – Fuel and performance data for nuclear reactors

	PWR	BWR	APWR	GCR	PHWR	PHWR	LWGR	FBR	HTGR
Fuel	UO2	UO2	UO2	UO2	UO2	UO2	UO2	UO2/MOX	UO2
Enrich %	3.50%	3.50%	4.50%	3.5%	0.72%	0.85%	2%	20.00%	8.0%
Burn-Up	45	45	60	38	8	11	20	100	90
Efficiency	32%	30%	35%	30%	32%	32%	28%	40%	42%

Source: Adapted from IAEA, 2015b

In chapter 4, the uranium resources and cost of extraction were presented. In Table 5-7 the standard costs for producing nuclear fuels used in this study are presented. The data are based on data from WISE (2016). It considers both production costs and costs relating to waste management separately.

Table 5-7 - Costs from the nuclear fuel chain

Process	Unit	Fuel Prod. Cost	Waste Mgmt Cost
Conversion	$/kg U	7	0
Enrichment	$/SWU	60	0
	$/kg U	0	10
Fuel Fabrication	$/kg U	460	0
Spent Fuel	$/kg U	0	840

Source: Adapted from WISE, 2016

Legend: SWU – Separation Working Unit

The level of enrichment and the production costs presented previously are the main drivers to estimating nuclear fuel costs. The material balance can be complex to estimate consistently. For this reason, the calculator available in WISE (2016) was used. The findings are presented in Table 5-8. This table also presents the estimates for reprocessing depleted uranium into nuclear fuel.

Table 5-8 – Material balance and production costs for nuclear fuel

Enrichment	%	0.72%	0.85%	2.00%	3.50%	4.50%	8.00%	20.00%	3.50%	MOX
Input Type		Natural	Natural	Natural	Natural	Natural	Natural	Natural	Depleted	Depleted
Input	t U	0.995	0.995	0.995	0.995	0.995	0.995	0.995	1.000	1.000
Fuel	t U	0.964	0.736	0.238	0.127	0.096	0.053	0.021	0.195	1.059
Waste	t U	0.021	0.251	0.754	0.867	0.898	0.942	0.974	0.805	0.000
Cost	$/kg U	460.2	462.5	467.5	468.7	469.0	469.4	469.7	5.1	1247.0
SWU	SWU/t U	6.2	85.2	408.4	554.6	606.7	700.4	795.4	157.6	45.5

Source: Adapted from WISE, 2016

Legend: SWU – Separation Working Unit

Regarding liquid fuels, besides oil products, two alternatives sources of liquid fuels are considered: synthetic fuels and biofuels. The latter will be presented in the next chapter, together with all bioenergy technologies. As for synthetic fuels, two main sources of fuel are considered, both with or without carbon capture: coal and biomass.

The technical parameters and carbon balance for all technologies are presented in Table 5-9. It is worth noting that all processes present CO_2 emissions related to the Fischer-Tropsch process. Also, specifically for biomass with CCS, the overall emissions are negative, being one of the BECCS options available in the model.

Table 5-9 – Gasification with Fischer-Tropsch technologies

Tech.	Fuel Input CCS		Coal w/o CCS	Coal w/ CCS	Biomass w/o CCS	Biomass w/ CCS
Input	Coal	PJ/y	25.2	25.2		
	Biomass	PJ/y			21.4	21.4
Output	Elect	PJ/y	3.2	2.7	3	2.4
	Gasol	PJ/y	2	1.8	1.6	1.4
	Diesel	PJ/y	10.3	10.5	8.2	8.3
Carbon Balance	Emitted	kt C/y	376	42	360	33
	Product	kt C/y	217	217	174	173
	Stored	kt C/y		334		328

Source: Adapted from MEERMAN *et al.*, 2013

As for gaseous fuels, the only options presented in this section are related to hydrogen technologies. That being said, synthetic natural gas technologies were not addressed in this study. Despite that, they can be easily introduced into the modelling framework in future studies.

As for the Hydrogen production technologies, there are 7 technologies available, which are presented in Table 5-10. The most common technology for hydrogen production is the natural gas reforming. This technology can also be coupled with carbon capture, in order to reduce carbon emissions.

Alternative technologies include coal to hydrogen (CTH) and biomass to hydrogen (BTH), with or without carbon capture. Finally, the last option for hydrogen production is the Electrolysis process, which uses electricity to split water molecules.

Table 5-10 – Hydrogen technologies

Aspect	Unit	NG Ref.	NG Ref. CCS	CTH	CTH CCS	BTH	BTH CCS	Electrolysis
Energy Input		Natural Gas	Natural Gas	Coal	Coal	Biomass	Biomass	Electricity
Efficiency (LHV)	% (LHV)	74	74	59	59	83	83	67
CO2 Emissions	t/GJ	0.076	0.021	0.160	0.009	0.000	0.000	0.000
CO2 Captured	t/GJ	0.000	0.052	0.000	0.151	0.000	-0.114	0.000

Source: Adapted from LINDSAY *et al.* (2009), INL, 2010, DAIOGLOU (2016)

5.3. Transportation Sector

This section presents how the Transportation sector was introduced into the model, both in terms of structure and demand. The basic characteristics of this sector is that there is no specific product related to this activity. This sector actually is responsible

for providing a service, either to individuals (namely passengers) or goods and products (namely freight).

According to IPPC (2007), transportation is a key component of economic development and human welfare, which increases as economies grow. For most policymakers, the most pressing problems associated with this increasing transport activity are traffic fatalities and injuries, congestion, air pollution and petroleum dependence.

The activity of the transportation sector is usually separated into passenger and freight. The activity of the former is represented in passenger-km, or pkm, which is a measurement of the total distance required by the total number of passengers.

As for freight, the unit used to represent the activity is tonne-km, or tkm. In this activity indicator, all goods and products are combined into the total weight being transported by the total distance.

The activity, either in pkm or tkm, is the expression of the energy service from the transportation sector. In other words, the energy consumed in this sector is used to achieve a necessary level of activity. In this sense, within the model, the exogenous demand will be expressed in pkm, for passengers, and tkm, for freight.

The main input data used in the global IAM developed in this study, which will be presented briefly in this section, were based on a model from the International Council on Clean Technology[6] (ICCT, 2012). It is an open source software exclusively for the global transportation sector. The ICCT's Global Transportation model is a tool developed to help policy makers worldwide identify and understand trends in the transportation sector, assess emission effects of different policy options, and frame plans to effectively reduce emissions of both greenhouse gases (GHGs) and local air pollutants (ICCT, 2012).

The transportation modes included in the model are: Light Duty Vehicles (LDVs, including SUVs), buses, 2-wheelers (2W), 3-wheelers (3W), Light Heavy Duty Trucks (LHDTs) (5,750 – 14,000 lbs), Medium HDTs (MHDTs) (14,000 – 33,000 lbs), Heavy HDTs (HHDTs) (>33,000 lbs), passenger rail, freight rail, aviation (passenger only), and Marine for freight only (ICCT, 2012).

The model is originally represented in 11 regions, but that was adapted to incorporate all 18 regions of the model developed in this study. The original regions,

[6] The model and supporting documentations are posted on our website - www.theicct.org/transportation-roadmap.

which are not very different from the ones used in this study, are: United States, EU-27 (27 member states included in the European Union), China, India, Japan, Brazil, South Korea, Mexico, Canada, Australia, Russia, Latin America, non-EU Europe, Asia-Pacific, Africa, and the Middle East.

As for technologies, the model considers a wide range of options, such as conventional (internal combustion engine), hybrid, plug-in hybrid, fuel cell, and battery electric vehicles. In terms of fuels, most of the options are related to road vehicles, which include: diesel (conventional, low-sulphur), ethanol (grain, sugarcane, cellulosic), biodiesel (oil-based, lingo-cellulosic), Natural Gas, LPG, hydrogen, electricity, jet fuel, and fuel oil.

The model has a lot of input data. However, most of them were kept at their default values, and using the values of one of the 11 original regions as a proxy for the additional 7 regions. On the other hand, the input of socioeconomic data, such as GDP and population, were modified in order to estimate the future demand of energy services.

The model has a series of econometric methods in order to estimate the demand of energy services for transportation of passengers (PKM) and freight (TKM). Based on the analysis of historical data, the model uses a constant elasticity for mobility per capita relative to income and population.

In simple terms, the population projections are used in combination with GDP and relative fuel price forecasts, taken from the scenarios within IEA (2011), to predict future transportation activity. The relationships between these factors are assessed through a series of Gompertz functions, as follows:

$$y(x) = a \cdot b^{c^x}$$

Where:

$0 < a < 1$ – is the upper limit which the function reaches asymptotically;

$0 < b < 1$ – where $a \cdot b$ is the initial value (at $t = 0$);

$0 < c < 1$ – is the growth indicator (small values increase rapidly; large values increase slowly);

$x > 0$ – is the independent variable (e.g.: time).

Thus, unlike the next sector of the economy addressed in this chapter, the demands for energy services of the transportation sector were estimated through a third-party tool,

using method and assumptions outside the scope of this study. The results are shown in Table 5-11, for passenger transportation, and in Table 5-13, for freight transportation.

Table 5-11 – Passenger demand (G PKM)

Gpkm	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	1524	1815	2333	3160	4533	6799	10218	14584	18694	20922
AUS	337	460	601	750	896	1043	1188	1326	1443	1531
BRA	1541	1862	2251	2689	3257	3882	4377	4812	5172	5447
CAM	1006	1249	1640	2136	2730	3339	3928	4526	5088	5579
CAN	696	839	997	1174	1338	1505	1675	1842	1986	2097
CAS	1061	1347	1905	2695	3782	5261	7071	9138	11259	13197
CHN	9769	16934	26102	31508	33972	34426	33814	32796	31522	30224
EEU	6748	7970	9801	11836	13758	15626	17376	19094	20655	21996
IND	4441	10211	12889	16596	20906	26098	31821	37296	42005	45612
JPN	1446	1389	1311	1260	1212	1177	1137	1118	1104	1095
KOR	817	967	1113	1229	1288	1300	1280	1254	1220	1182
MEA	1401	2255	3609	5184	6690	8131	9479	10726	11766	12533
RAS	3120	3731	4968	6618	8714	11423	14516	17762	20788	23282
RUS	1139	1831	2357	2787	3086	3392	3710	3981	4195	4361
SAF	79	84	94	114	149	210	304	437	605	789
SAM	1688	2289	3066	3987	5046	6157	7172	8078	8808	9352
USA	7706	9109	10439	11807	13033	14233	15381	16486	17455	18286
WEU	1162	1538	2052	2324	2465	2586	2680	2757	2815	2859

The ICCT model also provides the necessary information regarding historic fleet, technical parameters of technologies and estimates for fuel prices. For instance, Figure 5-14 presented the composition of the transportation modes used in the base year.

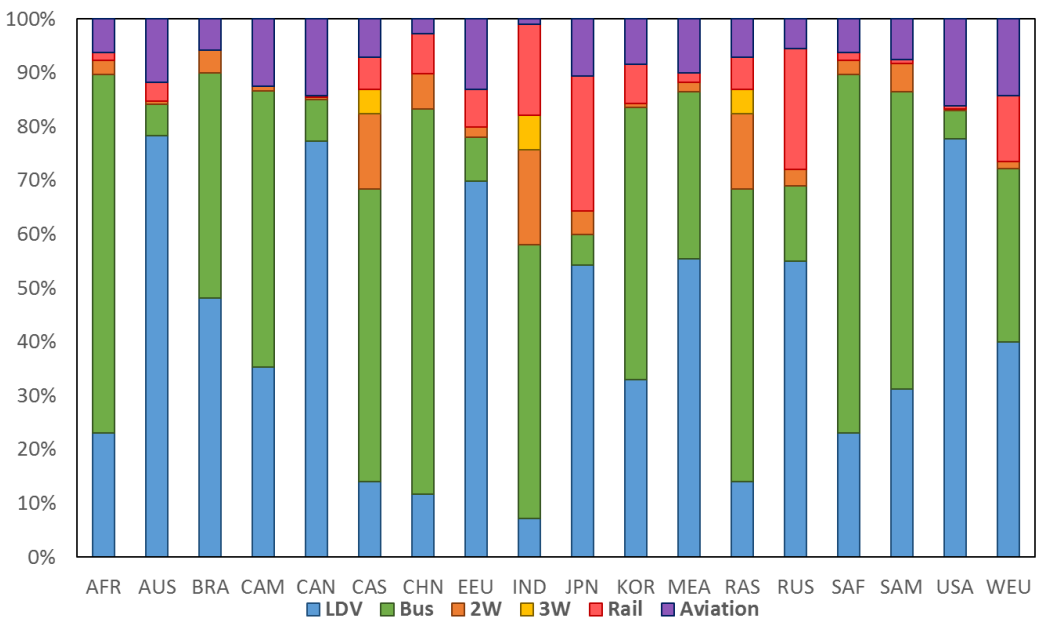


Figure 5-14 – Base year distribution of passenger demand

Legend: LDV (Light Duty Vehicle); 2W (Two Wheels); 3W (Three Wheels)

There are few interesting facts to be extracted from this figure, such as the relatively high participation of Light Duty Vehicles (LDV) and buses, combined, which ranges from near 60% to roughly 90% across all regions. However, the individual contribution of LDV and buses vary widely.

Another interesting fact is the participation of 2 wheel vehicles (motorcycles) across regions. Even more notable is the importance of 3 wheel vehicles in very few regions, such as India and Asian regions.

However, the technological detail provided by the ICCT tool goes even further than that. The model provides regional information on occupancy factor (passenger per vehicle) and typical mileage (km per year) for every transportation mode, as well as efficiency and fleet composition in terms of fuel and technology, used. For instance, Table 5-12 presents the breakdown at base year for the LDV and Bus fleet.

Table 5-12 – LDV and Bus Fleet breakdown by region and fuel (%)

	LDV Base Year (% Fleet)			
	ICE Gasoline	ICE Diesel	ICE GNV	ICE LPG
AFR	95.6	4.4	0.0	0.0
AUS	94.2	2.6	1.6	1.6
BRA	98.2	0.0	0.9	0.9
CAM	96.8	0.6	1.3	1.3
CAN	97.6	1.7	0.3	0.3
CAS	93.5	6.4	0.0	0.0
CHN	95.9	0.0	2.0	2.0
EEU	79.8	18.9	0.6	0.6
IND	75.2	20.1	2.3	2.3
JPN	85.2	11.6	0.3	3.0
KOR	85.5	7.3	3.6	3.6
MEA	95.0	5.0	0.0	0.0
RAS	93.5	6.4	0.0	0.0
RUS	97.9	1.2	0.5	0.5
SAF	95.6	4.4	0.0	0.0
SAM	91.8	7.0	0.6	0.6
USA	97.3	2.6	0.0	0.2
WEU	92.2	7.8	0.0	0.0

	Bus Base Year (% Fleet)			
	ICE Gasoline	ICE Diesel	ICE GNV	BAT Ele
AFR	20.0	80.0	0.0	0.0
AUS	15.0	85.0	0.0	0.0
BRA	20.0	80.0	0.0	0.0
CAM	25.0	75.0	0.0	0.0
CAN	5.8	85.1	2.8	6.4
CAS	30.0	70.0	0.0	0.0
CHN	79.0	21.0	0.0	0.0
EEU	15.0	85.0	0.0	0.0
IND	5.0	95.0	0.0	0.0
JPN	0.3	99.7	0.0	0.0
KOR	15.0	85.0	0.0	0.0
MEA	30.0	70.0	0.0	0.0
RAS	30.0	70.0	0.0	0.0
RUS	20.0	80.0	0.0	0.0
SAF	20.0	80.0	0.0	0.0
SAM	20.0	80.0	0.0	0.0
USA	4.0	92.4	3.6	0.0
WEU	20.0	80.0	0.0	0.0

Source: ICCT, 2012

Legend: ICE (Internal Combustion Engine); GNV (Gas Natural in Vehicles)

Table 5-13 – Freight demand (TKM)

Gtkm	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	408	518	685	935	1318	1884	2638	3440	3994	4135
AUS	412	461	518	576	635	694	754	808	853	887
BRA	994	1093	1208	1336	1509	1705	1875	2033	2180	2313
CAM	220	297	410	554	732	924	1124	1333	1542	1739
CAN	559	607	667	733	796	858	925	988	1039	1078
CAS	240	318	436	579	767	1036	1414	1888	2432	3011
CHN	4478	6455	9149	10955	11970	12353	12394	12214	11908	11560
EEU	2926	3323	3950	4656	5350	6036	6726	7349	7899	8352
IND	1612	3882	4649	5696	6904	8365	10033	11675	13194	14507
JPN	356	350	331	310	288	265	241	216	190	166
KOR	78	139	198	249	282	300	305	304	296	284
MEA	359	622	1046	1564	2090	2627	3187	3742	4276	4740
RAS	1027	1274	1691	2245	2947	3843	4874	5964	7042	8016
RUS	2086	2255	2416	2551	2649	2752	2868	2963	3041	3105
SAF	133	150	172	203	242	294	365	453	554	656
SAM	369	544	766	1034	1353	1704	2052	2379	2669	2915
USA	4236	4777	5344	5894	6397	6870	7337	7744	8079	8339
WEU	500	629	800	910	980	1042	1100	1136	1152	1151

As for freight transportation, the ICCT model has fewer transportation modes and technologies than for passengers. Figure 5-14 presents the distribution of modes that add up to the total demand. The data shown are related to base year only.

The figure can also be used to infer on the relative energy intensity of the freight transportation. For instance, generally, a region with higher participation of rail presents a lower intensity, than one with higher participation of road-based freight, especially with lighter duty trucks.

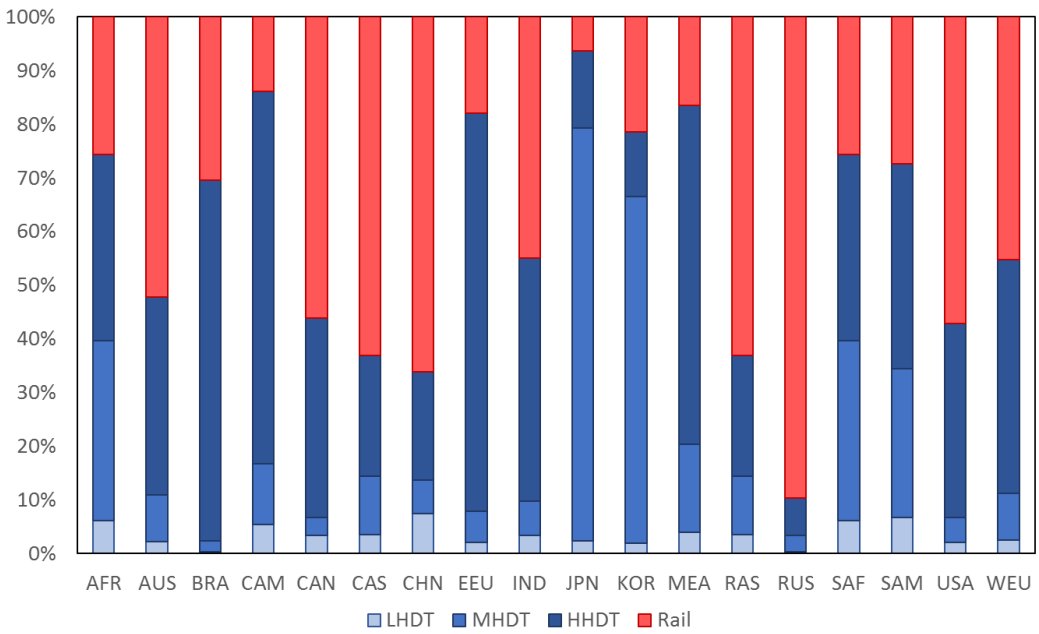


Figure 5-15 – Base year distribution of Freight demand

Legend: LHDT (Light Duty Truck); MHDT (Middle Duty Truck); HHDT (Heavy Duty Truck)

Just as for the passenger technologies, the ICCT model provides regional data on occupancy and typical mileage for all three truck sizes and rail. Also, historical data for fleet of freight technologies, separated by fuel. Nonetheless, across all regions the large majority of the fleet of trucks are diesel-based.

Additionally, a few mitigation options were introduced to the model. The first mitigation option is related to shift in transportation modes, more specifically from lower efficiency modes into higher efficiency modes.

In order to assess this option, the ICCT model was used in an alternative scenario in order to provide guidelines for how the transportation modes shift in time. For instance, if a given region increases LDVs or buses in the demand share. The model was used to create a lower and upper bounds of mode shifts. For transportation, the only shift available was between buses and LDVs. As for freight, the only shift available was between heavy duty trucks and rail.

Another important mitigation option made available to the model is the introduction of alternative technologies (electric and fuel cell vehicles) and fuels. The latter includes the opportunity to increase biofuel use, either directly or in blends with conventional fuels.

Despite the introduction of these mitigation options, other options were not added at this point into the model. For instance, two other options that could be assessed in the future are: reduction in activity due to logistic or infrastructure investments; increase in occupancy rates, which can be achieve if driven by specific policies.

5.4. Industrial Sector

The Industrial sector is the first sector from the sectorial composition of the GDP to be assessed in this chapter. Relatively to the other two (Agriculture and Services), it has a higher energy and emissions intensity. This obviously varies deeply in terms of what type of industry is portrait in the analysis, but it is generally true.

As mentioned, there are several types of industries within this sector, and they vary greatly in the production method, their processes and energy consumption and GHG emission. For instance, Paper and Pulp industry demand for energy is almost entirely provided by biomass and high energy content by-products from the pulp production process.

Steel production, however, depends highly on the process used in steelmaking. The electric arc furnace (EAF) uses electricity as the energy source and can use scrap metal as feedstock, whilst standard oxygen technology (Blast Furnace, or BOF) typically uses a fossil fuel, such as coal and charcoal, as both a reduction agent and energy source. It also makes steel from pig iron, instead of scrap metal.

Thus, each sub-industrial sector has its own energy and emissions profile, which can be analysed in great detail, as is the case of MESSAGE-Brazil. The Brazilian model has an 11 sub-industrial sector disaggregation, with highly detailed technology options, such as conversion technologies, energy efficiency options and different industrial processes (ROCHEDO *et al.*, 2015; KOBERLE *et al.*, 2015).

In global energy model, the assessment of the industrial sector is often simplified, such as in IIASA's MESSAGE-MACRO, where it is composed of only one overall industrial sector with a final energy demand (IIASA, 2013; IIASA, 2015). This is explained by the difficulty in assessing several industries, in great detail, for a great number of countries and regions of the world, where the detailed information needed are not easily available.

For instance, the International Energy Agency (IEA) compiles two major energy datasets that are useful for addressing this issue: Energy Statistics of OECD countries (IEA, 2011a; IEA, 2014a) and Energy Statistics of Non-OECD countries (IEA, 2011b; IEA, 2014b).

In these reports, for all OECD countries and a few of Non-OECD countries the industrial sector is split into 13 categories[7], whilst for the remaining countries it is split into only four[8] categories. The different levels in data aggregation hinders the consistent assessment of a region, such as Africa, due to two different datasets.

That being said, only a few regions proposed in this study would face the problem of different disaggregation level for industrial sector, mainly Africa (AFR), Rest of Asia and Oceania (RAS), Middle East (MEA), Central America (CAM) and Caspian (CAS). All these regions have a high participation of low income countries, which usually are amongst those with the lack of detailed information.

Nevertheless, at this point in time, a simplified approach for all 18 regions was used, considering only one industrial sector. This can, and should, be addressed in future studies to enhance the representation of the available technologies and mitigation options within the Industrial sector. Clearly, in order to have a consistent link between the economic development and the future energy demand of the several industrial sub-sectors, a more detailed disaggregation could be used.

5.4.1. Energy Consumption

As mentioned, the IEA database was used to estimate the global industrial energy consumption. The estimated regional consumption, by energy source, is presented in Table 5-14. Again, this table shows the aggregated consumption of the industrial sector for every region, i.e., without subsector disaggregation.

This is the first relevant information in order to model the behaviour of this sector within the model. Not only does it provide some information on the consumption profile

[7] Iron and Steel, Chemical and petrochemical, Non-ferrous metal, Non-metallic minerals, Transport equipment, Machinery, Mining and quarrying, Food and Tobacco, Paper and pulp, wood and wood products, construction, textile and leather, and non-specified.

[8] Iron and Steel, Chemical and petrochemical, Non-metallic minerals, Other industries.

of each region, it also establishes the consumption in the base year, 2010. It is worth noting the importance of China, of which most of the energy consumption is based on coal.

Table 5-14 – Industrial energy consumption for every region (PJ)

PJ	Coal Bet	Coal Lig	Coal Peat	CoalGas	Natural Gas	Crude	LPG	Lig Oil	Mid Oil	Hea Oil	Bio	Heat	Elect
AFR	32	14	0	16	684	0	14	2	256	170	885	0	421
AUS	139	43	0	23	444	2	14	1	129	38	152	0	411
BRA	115	34	0	83	346	0	34	0	33	365	1,446	0	735
CAM	46	55	0	2	626	63	53	2	142	286	154	0	539
CAN	51	22	0	40	1,187	0	40	0	110	44	311	27	611
CAS	382	170	0	3	726	0	0	3	79	45	135	175	371
CHN	15,913	3,282	0	3,616	882	108	21	0	1,051	560	14	1,697	8,768
EEU	554	542	19	235	3,560	76	167	84	558	605	918	649	3,882
IND	2,707	192	0	227	344	0	31	21	742	305	1,355	0	1,331
JPN	408	311	0	434	366	1	91	220	386	277	105	0	1,035
KOR	191	59	0	68	279	0	30	0	64	153	78	120	763
MEA	7	6	0	2	2,819	217	11	116	578	852	11	0	503
RAS	1,962	66	0	7	1,231	0	54	8	568	243	791	10	1,025
RUS	40	29	0	519	1,368	1	0	0	98	93	15	1,622	1,121
SAF	272	10	0	117	0	0	0	1	48	0	80	0	438
SAM	99	38	0	16	1,032	5	148	22	287	116	331	0	633
USA	727	89	0	57	4,712	0	29	147	769	148	1,191	215	2,756
WEU	56	148	2	143	399	0	1	3	55	29	17	264	321

Source: IEA (2011a;2011b)

5.4.2. Energy services

However, energy consumption alone is not the information needed to properly assess the sector. As previously explained, all energy sources are consumed within a sector in order to provide energy services.

In industrial facilities the most common energy services are related to heating (direct or indirect) and drive of machineries, such as engines and turbines. In this study, the categories of energy services available in IEA (2015) were used. They are: Heat, meaning direct heating; Steam, either for indirect heating or steam-driven engines; HVAC, or Heating, Ventilation and Air Conditioning of internal areas; Light; Motor, or the drive for electric motors; and other services.

Table 5-15, below, presents the estimated composition of the industrial energy consumption by all the energy services considered. It also presents a simplified approach, in which fuels for heating is separated from electricity, which can be used for all purposes.

Table 5-15 – Industrial energy consumption separated by energy service (%)

Region	Heat	Steam	HVAC	Light	Motor	Other	Fuel	Elect
AFR	70.0	13.5	5.6	5.6	3.2	2.0	83.1	16.9
AUS	42.2	26.5	6.3	5.2	17.6	2.1	70.6	29.4
BRA	48.8	28.0	5.2	6.5	9.5	2.0	77.0	23.0
CAM	42.1	29.9	5.4	5.9	14.6	2.0	72.6	27.4
CAN	47.4	25.8	6.1	0.7	17.2	2.7	75.0	25.0
CAS	82.9	0.0	4.9	6.6	3.5	2.0	82.3	17.7
CHN	73.8	1.4	5.3	0.6	16.1	2.9	75.6	24.4
EEU	58.4	7.1	6.3	5.1	19.9	3.3	67.2	32.8
IND	70.8	11.9	3.3	7.9	4.1	2.0	81.6	18.4
JPN	39.4	28.5	9.7	3.1	17.3	2.0	71.5	28.5
KOR	52.7	3.5	6.4	0.7	34.7	2.0	57.7	42.3
MEA	44.4	46.4	3.9	0.4	3.0	2.0	90.2	9.8
RAS	49.7	32.6	5.7	4.5	5.4	2.0	82.8	17.2
RUS	77.1	0.0	5.7	1.1	14.0	2.0	77.1	22.9
SAF	36.3	16.6	6.3	4.4	34.3	2.0	54.3	45.7
SAM	45.9	30.3	5.4	2.2	14.0	2.1	76.8	23.2
USA	49.1	25.4	5.4	7.8	6.9	5.3	74.6	25.4
WEU	78.1	0.2	4.6	3.8	11.3	2.0	77.7	22.3

Source: Adapted from IEA (2011a; 2011b) and IEA (2013)

Legend: HVAC (Heating, Ventilation and Air Conditioning)

The estimated energy service demand was made from data from IEA (2011a), IEA (2011b) and IEA (2013). The latter, provides a survey of energy services for a number of countries and regions. Since not all the 18 regions were properly addressed in the report, some assumptions had to be made, such as a similar profile of a given region and/or country. However, these proxy-profiles are usually not consistent with the energy consumption. As such, minor adjustments had to be made, which resulted in 18 different profiles.

Another interesting information which allowed for differentiating the profile of all 18 regions is the detailed data estimated for lighting. Relatively speaking, lighting is not the most energy consuming part of industry. As such, it is usually not easy to create estimates for detailed lighting demand within the industrial sector.

Nonetheless, through the assessment of several studies and reports (IEA, 2006; WINKLER, 2006; GELIL, 2011; INDIA, 2016; PROCEL, 2009), one of which is focused entirely on lighting, the following data, presented in Table 5-16, were able to be compiled.

Table 5-16 – Industrial lighting technology profile

	LED	Incandescent	Fluorescent	Avg Eff (lm/W)	IEA. 2004 (lm/W)
AFR	0%	25%	75%	61.3	
AUS	35%	0%	65%	80.3	80.0
BRA	0%	25%	75%	61.3	
CAM	0%	25%	75%	61.3	
CAN	30%	0%	70%	79.5	80.9
CAS	0%	25%	75%	61.3	
CHN	40%	0%	60%	81.0	
EEU	38%	1%	62%	80.4	80.0
IND	0%	25%	75%	61.3	
JPN	31%	2%	67%	78.6	81.6
KOR	31%	2%	67%	78.6	81.6
MEA	0%	25%	75%	61.3	
RAS	0%	25%	75%	61.3	
RUS	23%	10%	67%	73.0	
SAF	0%	25%	75%	61.3	
SAM	0%	25%	75%	61.3	
USA	30%	0%	70%	79.5	80.9
WEU	23%	10%	67%	73.0	
World	31%	2%	67%	78.6	79.0

Source: IEA, 2006; WINKLER, 2006; GELIL, 2011; INDIA, 2016; PROCEL, 2009

This table shows the estimated composition of technologies applied for industrial lighting (such as Incandescent, Fluorescent and Light Emitting Diode, or LED), as well as an average efficiency for lighting technologies. The calculated values are compared with available literature data for specific regions.

5.4.3. Industrial Demand

Finally, after establishing the energy service profile for every region, a set of energy intensities were estimated. These intensities relate the energy service demand with the Industrial GDP of a single region. These values were used to estimate future industrial energy demands within the model.

Since the demands are exogenous to the model, they were calculated in spreadsheets, with the intensities presented in Table 5-17, and used as input data in the model. The results are presented in Figure 5-20, which shows the evolution of the energy service demand until 2100. From this figure, it is clear that direct heating is the most

important service required by the industrial sector. Lighting demand is not presented because of the different unit used for this service, which is G lumen-year.

Table 5-17 – Energy service intensities for every region at base year

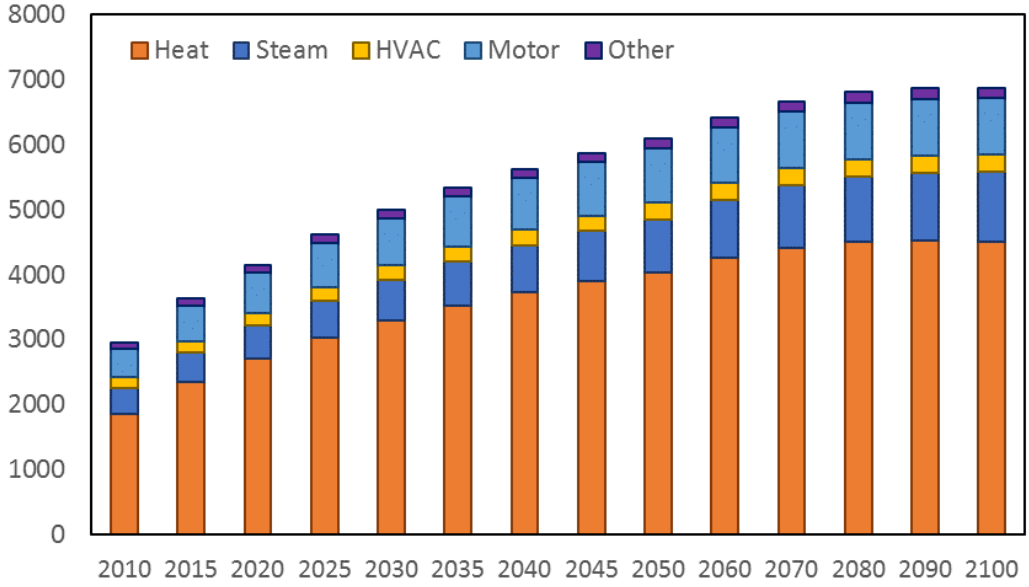
MWyr/ GUS$(IND)	Useful Energy					
	Heat	Steam	HVAC	Light	Motor	Other
AFR	136.0	26.0	11.2	0.8	7.4	4.8
AUS	91.4	57.2	13.3	1.0	43.0	5.1
BRA	127.2	71.8	14.0	1.3	31.3	6.7
CAM	59.5	42.0	7.5	0.6	23.2	3.2
CAN	85.7	46.5	10.8	0.1	34.7	5.5
CAS	469.2	0.2	26.6	2.5	21.9	12.4
CHN	420.3	8.1	28.7	0.3	101.0	18.0
EEU	47.9	5.7	5.0	0.4	18.1	3.0
IND	405.0	67.4	18.5	3.2	27.7	13.4
JPN	31.6	22.8	7.5	0.2	15.6	1.8
KOR	68.6	4.5	8.1	0.1	50.2	2.9
MEA	99.6	103.7	8.4	0.1	7.3	4.9
RAS	160.6	104.6	17.9	1.0	20.0	7.3
RUS	349.5	0.1	24.5	0.4	67.7	9.7
SAF	113.1	51.0	18.4	1.0	121.5	7.1
SAM	124.3	81.8	14.4	0.4	42.6	6.4
USA	56.7	31.3	6.3	0.8	9.2	7.0
WEU	433.9	0.8	24.7	1.7	67.6	12.0
World	130.9	28.1	11.2	0.6	31.0	6.6

* Demand in Glmyr/GUS$(IND)

Legend: HVAC (Heating, Ventilation and Air Conditioning)

The basic assumption is that these intensities will not change throughout time. Basically, the energy demand increases, because industrial GDP increases. However, the structure of the industrial sector remains constant, which in turn keeps the energy service demand relatively constant. This is a major assumption, which can only be properly tackled by disaggregating the industrial sector and maintaining a consistent evolution with the economic development. This can only be achieved through, and is the main advantage of, an IAM.

Table 5-18 – Global Industrial energy service demand (except Lighting) in GWyr



5.4.4. Non-energy demand

Besides energy consumption, the industrial sector also presents a consumption of typically energy sources as non-energy inputs. This includes naphtha, from refineries, natural gas and even coal. Typically, these products are used as feedstock in industry processes, such as ammonia and petrochemical production. The non-energy consumption does not result in energy-related emissions, but it is an important part of the total consumption of energy products.

The estimated profile and total consumption of non-energy products are presented in Table 5-19 and Table 5-20. It is clear that natural gas and naphtha (presented as gasoline in Table 5-19) are the most important sources of non-energy products. The estimated future demand for non-energy products are estimated from the consumption intensity in the base year.

Table 5-19 - Industrial non-energy distribution for every region

Region	Bet. Coal	Sub. Coal	Lignite	NG	LPG	Gasoline	Kerosene	Diesel	Fuel Oil	Pet Coke	Biomass	Charcoal	Elect	Heat
AFR	0.0	0.0	0.0	80.5	0.8	13.2	0.2	0.0	0.0	4.0	1.3	0.0	0.0	0.0
AUS	0.0	0.0	0.0	49.3	24.3	0.0	0.2	0.0	0.0	24.2	2.1	0.0	0.0	0.0
BRA	1.4	0.0	0.0	8.5	0.0	85.9	0.1	0.0	0.0	0.0	1.6	0.0	0.0	0.0
CAM	0.0	0.0	0.0	81.7	16.7	1.2	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
CAN	1.7	0.0	0.0	18.9	53.5	17.2	0.0	0.0	0.0	7.7	1.1	0.0	0.0	0.0
CAS	7.7	0.0	0.0	86.0	0.1	3.9	0.0	0.2	1.4	0.1	0.6	0.0	0.0	0.0
CHN	32.7	0.0	0.1	8.2	1.3	48.3	0.0	0.4	1.6	6.7	0.7	0.0	0.0	0.0
EEU	1.0	0.0	0.5	21.0	12.9	52.9	0.5	3.8	4.1	1.9	1.2	0.0	0.0	0.0
IND	0.0	0.0	0.0	49.8	0.0	32.1	0.0	0.0	0.0	17.0	1.1	0.0	0.0	0.0
JPN	0.8	0.0	0.0	2.1	13.9	77.7	2.2	0.7	1.0	1.1	0.5	0.0	0.0	0.0
KOR	0.9	0.0	0.0	0.0	5.5	93.3	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0
MEA	0.0	0.0	0.0	67.6	25.4	6.4	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0
RAS	0.0	0.6	0.0	49.4	12.4	37.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0
RUS	0.4	0.0	0.0	59.3	13.9	26.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
SAF	91.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.1	0.0	0.0	0.0
SAM	0.0	0.0	0.0	54.6	28.4	14.9	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0
USA	0.0	0.0	0.0	11.6	66.4	13.3	0.0	0.0	0.0	7.5	1.2	0.0	0.0	0.0
WEU	18.4	0.0	0.5	74.1	0.8	4.5	0.0	0.1	0.2	0.0	1.2	0.0	0.0	0.0

Source: Adapted from IEA (2011a;2011b)

Table 5-20 – Industrial non-energy demand by region (MWyr)

Mwa	2010	2015	2020	2025	2030	2035	2040	2045	2050	2060	2070	2080	2090	2100
AFR	10006	12193	14664	17532	20811	24476	28586	33119	38012	48471	58865	67705	73664	76275
AUS	3484	3877	4251	4620	4954	5260	5550	5830	6092	6606	7118	7578	7970	8303
BRA	11749	12697	13638	14706	15648	16464	17155	17711	18111	18481	18516	18427	18451	18756
CAM	23014	25014	26919	29169	31236	33075	34688	36056	37180	38793	40132	41788	44105	47204
CAN	18743	19966	21356	22796	24176	25509	26769	27929	28980	31006	33141	35084	36699	38025
CAS	8886	11138	13586	16247	18826	21273	23666	26070	28513	33573	38666	43111	46371	48158
CHN	154522	217492	253048	279577	297208	308379	314857	317867	317756	310696	298872	285035	270835	258264
EEU	104761	109579	116308	123872	131275	138366	145137	151437	157222	168172	178766	188274	197095	205275
IND	37817	50853	65257	80545	94691	107572	119365	130171	139985	155986	165696	169006	166565	160252
JPN	46769	45562	44519	43945	43475	42911	42293	41754	41263	40625	40192	39764	39529	39513
KOR	47553	51935	56071	60020	63800	67303	70366	72990	75136	78383	80682	82699	84438	85768
MEA	74534	85515	96569	108992	121964	134800	147299	159167	170238	190833	209956	228124	246722	266299
RAS	38056	45648	53935	62635	70870	78499	85631	92101	97977	107379	112927	114767	113676	110955
RUS	66606	71280	74493	78016	80813	83096	85071	86664	87909	89981	91693	92893	93911	95152
SAF	1598	1740	1877	2034	2174	2293	2395	2480	2554	2682	2798	2917	3055	3209
SAM	6699	7619	8436	9291	10089	10819	11477	12064	12568	13293	13672	13788	13758	13717
USA	116753	121004	127339	133335	138593	143619	148457	153110	157260	165808	175101	183978	192349	200193
WEU	9504	10843	12011	13183	14123	14886	15529	16072	16525	17203	17517	17548	17467	17408

5.4.5. Industrial process emissions

The energy and non-energy demand of the industry sector were assessed in the previous section. As mentioned, energy consumption is directly related to GHG emissions. However, there are still GHG emissions sources in the industrial sector that are not related to energy consumption. They are the industrial process emissions.

These emissions sources are intrinsic to the production process of several products, such as cement, ammonia and steel. For instance, in 2010 the Brazilian industrial energy-related emissions were estimated at around 99 $MtCO_2$, and the industrial process emissions at around 75 $MtCO_2$ (MCTI, 2013).

The main sources of process GHG emissions are cement (Clinker) and steel production. The latter is directly dependent on the process. For instance, BOF process have the higher emission factor, whilst EAF process does not contribute with any GHG emission. As such, the cement production and steel making production through BOF process are used as the only sources of industrial process emissions.

The global clinker production, both historical and for the base year, was estimated with data from the United States Geological Service. The time series available in USGS (2013), which includes 215 countries, was used to estimate the future production of cement from all 18 regions of the model.

By using the time series, the historic profile was used to estimate a production intensity, related to the Industry GDP (tonne of product per Industry GDP). Therefore, using the macroeconomic scenario, the future production of cement was estimated. Emission factors were estimated from IPCC (2006) and GCA (2016), with mean value of 0.55 tCO_2/t of clinker.

As for the global steel production, the most comprehensive data available found are from the World Steel Association (WSA, 2014). The database includes 107 countries and disaggregates production in three technologies: Oxygen (BOF), EAF, and Open Hearth. The estimated production of steel was based on production intensity, just like for the cement production. The emission factors were estimated from IPCC (2006) and WSA (2014).

Finally, Table 5-21 presents the estimated CO_2 emissions from cement and steel production in the base year, and Figure 5-16 presents the estimated future production of clinker and steel in BOF.

Additionally, an abatement option for industrial process emissions was considered: carbon capture. Thus, at an additional cost and with an energy penalty, the industrial process emissions can be reduced greatly. The emissions factors and costs were estimated from OLIVEIRA (2015) and ROCHEDO *et al.* (2016).

Table 5-21 – Estimated process CO_2 emissions by source and region ($MtCO_2$)

Region	Cement	Iron
AFR	65.5	1.3
AUS	4.2	7.8
BRA	29.8	30.8
CAM	25.0	6.6
CAN	5.8	9.0
CAS	24.0	0.0
CHN	917.4	722.6
EEU	112.1	139.5
IND	110.8	27.3
JPN	24.0	106.2
KOR	23.9	44.9
MEA	78.9	2.4
RAS	95.1	27.3
RUS	22.9	55.5
SAF	5.5	5.7
SAM	25.0	4.0
USA	31.6	39.6
WEU	9.4	31.9

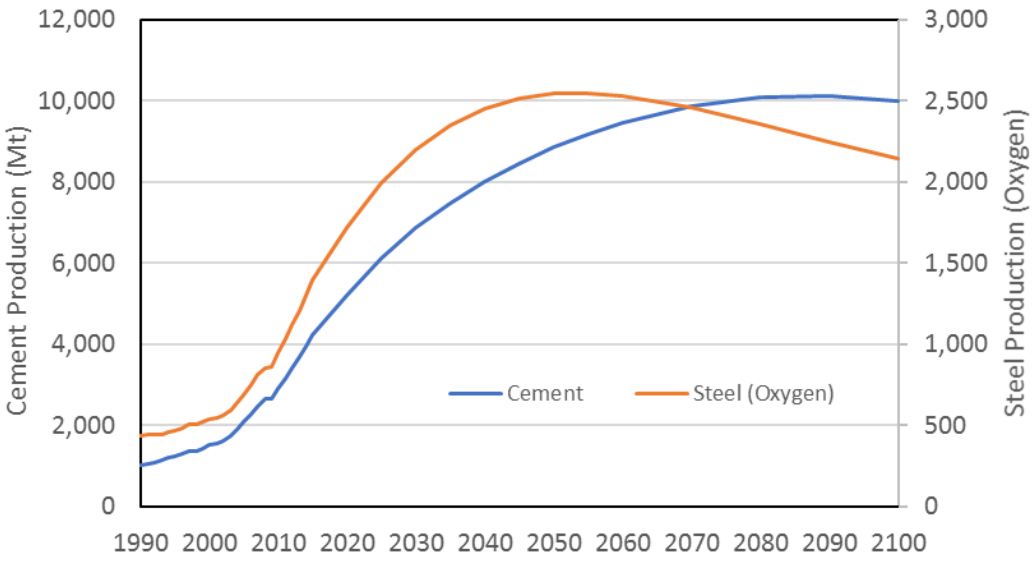


Figure 5-16 – Cement and Steel production (Oxygen)

Source: Estimated from USGS (2013), WSA (2014) and GCA (2016)

5.5.Residential Sector

This section explores the residential sector, or the household sector. It is the second largest consumer of electricity worldwide, with almost 30% of total final consumption (IEA, 2011a; IEA, 2011b). It has a great importance both in social and economic aspects, since it comprises the source of labour of the economy, one of the most important production factor commonly attributed to economic growth and production. Besides, HHE is also the majority of the GDP, expenditure-wise.

The energy consumption of this sector is directly related to population size. However, the social structure and welfare, and consumption behaviour, are extremely important to determine the consumption profile. Also, other effects play a major role, such as weather conditions, architecture, infrastructure and market failures (e.g. subsidies).

In order to address all these effects systematic and consistently, the approach used in this study is similar to the one used for the industrial sector. However, the difference relies on the fact that instead of using population or HHE as a driver for energy consumption, the selected drive is indirectly linked: household number, or more generally speaking, dwellings.

5.5.1. Dwellings estimates

So, the first step in the assessment of the residential sector is to estimate the total number of dwellings for all regions. The simplest approach is to use the mean value of habitants per dwelling. In UNSTAT (2015) this coefficient can be determined for 78 countries, which was used to estimate the mean value for every region. The findings are available in Table 5-22.

Table 5-22 – Estimated habitants per dwelling

Region	hab/res
AFR	4.74
AUS	2.74
BRA	3.33
CAM	3.99
CAN	2.69
CAS	4.61
CHN	3.34
EEU	2.87
IND	4.54
JPN	4.82
KOR	3.56
MEA	3.68
RAS	4.60
RUS	3.04
SAF	4.01
SAM	4.28
USA	3.02
WEU	3.04
World	4.07

Source: UNSTAT, 2015

As such, this coefficient was used to estimate the number of dwellings per region. The population vector was already presented in previous sections. However, instead of using the coefficient as constant, the future socioeconomic conditions may change the social dynamics. In order to estimate the changes of the number of inhabitants per dwellings, a correlation between this coefficient and HHE was determined. Figure 5-17 presents the findings. Using the correlation, the total number of dwellings was estimated. The results for dwellings are available in Figure 5-18.

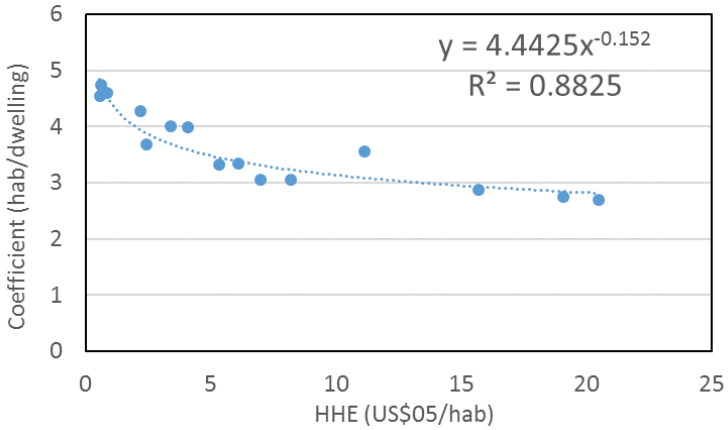


Figure 5-17 – Correlation between dwellings and HHE

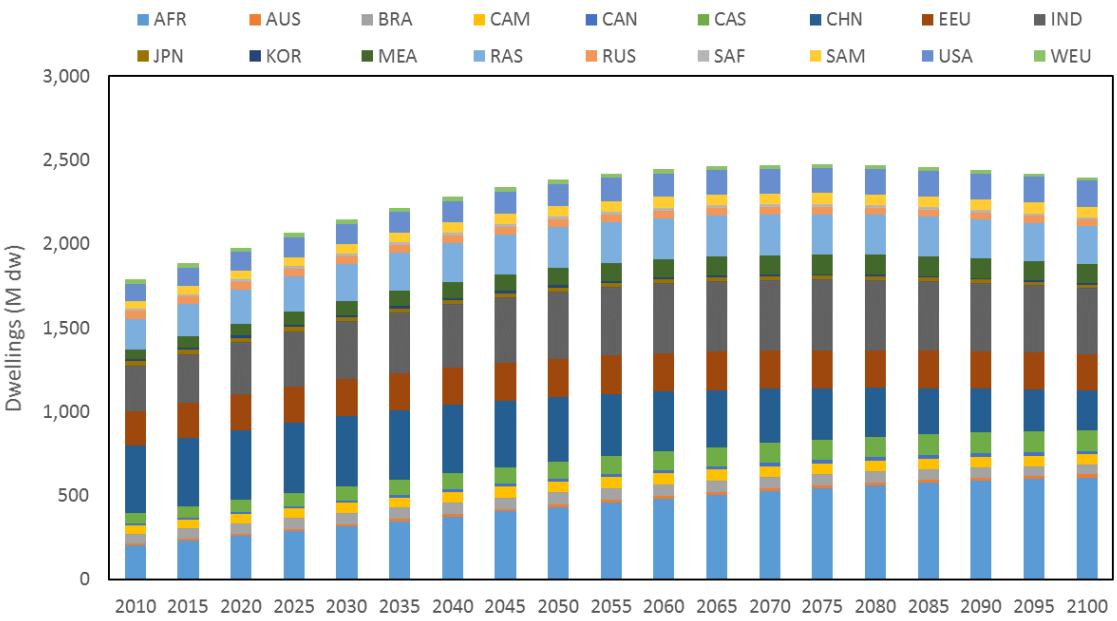


Figure 5-18 – Estimated number of dwellings across regions

5.5.2. Energy Consumption

Just as for the Industrial sector, the IEA database (IEA, 2011a; IEA, 2011b) was used to estimate the energy consumption in the residential sector. The estimated regional consumption, by energy source, is presented in Table 5-23. The main energy sources are electricity, natural gas and biomass.

Table 5-23 – Energy consumption for household at base year (PJ)

PJ	Bet. Coal	Sub. Coal	Lignite	NG	LPG	Gasoline	Kerosene	Diesel	Fuel Oil	Coke	Biomass	Charcoal	Elec.	Heat
AFR	0.4	0.0	3.4	266.8	397.4	0.0	113.0	86.6	0.0	0.0	7589.0	392.2	435.9	0.0
AUS	0.3	0.6	0.5	146.6	15.3	0.0	0.0	1.5	0.0	0.0	63.0	0.0	259.8	0.0
BRA	0.0	0.0	0.0	10.5	256.8	0.0	0.0	0.0	0.0	0.0	299.9	39.8	366.4	0.0
CAM	2.8	0.0	0.0	46.3	319.5	0.0	1.7	0.7	0.0	0.0	713.9	7.3	271.8	0.0
CAN	0.0	0.0	1.8	660.4	12.8	0.0	9.9	272.7	1.0	0.0	83.8	0.0	576.9	0.0
CAS	53.3	0.0	12.1	1053.4	27.2	2.2	2.7	9.5	12.6	0.0	1078.9	12.4	241.2	88.1
CHN	2402.8	0.0	170.5	726.2	744.6	0.0	3.2	348.8	0.0	0.0	8266.2	157.4	1948.0	670.0
EEU	460.8	3.7	255.1	5643.2	343.1	38.2	509.9	5635.0	47.2	0.0	1619.8	1.9	3360.2	861.4
IND	153.3	0.0	15.1	1.0	576.0	0.0	166.8	0.0	0.0	0.0	5338.1	76.5	525.9	0.0
JPN	0.0	0.0	0.0	420.7	189.9	0.0	220.9	0.0	0.0	0.0	0.9	0.0	1029.7	1.3
KOR	0.0	0.0	57.3	384.6	27.5	0.0	68.4	22.6	3.9	0.0	1.0	0.0	207.7	64.5
MEA	0.4	0.0	0.0	1629.2	369.5	0.0	183.8	69.3	0.0	0.0	5.2	0.3	1022.2	0.0
RAS	53.1	0.0	14.3	87.3	319.0	0.0	64.3	5.9	0.5	0.0	4632.8	167.3	649.7	15.0
RUS	81.0	0.0	8.5	1939.0	132.6	0.0	0.0	75.0	15.4	0.0	36.8	0.4	445.7	2085.5
SAF	191.5	0.0	0.0	0.0	9.2	0.6	10.2	0.0	0.0	0.0	350.2	8.8	141.1	0.0
SAM	3.7	0.0	0.0	445.9	257.6	0.0	0.1	0.3	38.0	0.0	370.6	18.9	376.3	0.0
USA	0.0	0.0	0.0	5167.8	288.7	0.0	64.0	1745.7	0.0	0.0	411.1	19.9	4904.1	0.0
WEU	31.8	0.9	74.3	725.9	45.1	17.4	0.2	20.0	0.8	0.0	82.2	0.8	237.6	274.4

Source: Adapted from IEA (2011a;2011b)

5.5.3. Energy Service

As mentioned earlier, there are several factors which influence the energy consumption profile of a region. However, the energy consumption is actually driven by the energy services required by the households. The disaggregation of the energy consumption in energy service terms is presented in Table 5-24.

Table 5-24 - Household energy consumption separated by energy services (%)

Region	Space H	Water H	Cook	Light	App	Cooling	Fuel	Elect
AFR	20.9	4.7	65.1	2.3	4.7	2.3	92.4	7.6
AUS	37.7	22.9	4.9	6.3	25.2	3.0	48.9	51.1
BRA	0.1	8.0	60.0	8.0	21.9	2.0	62.4	37.6
CAM	4.0	10.0	65.0	6.0	13.0	2.0	80.2	19.8
CAN	60.0	17.0	4.0	4.0	13.0	2.0	61.6	38.5
CAS	59.0	10.0	20.0	5.0	5.0	1.0	89.7	10.3
CHN	29.6	6.5	55.0	2.5	4.8	1.6	90.5	9.5
EEU	58.5	17.0	3.8	5.7	13.2	1.9	73.8	26.2
IND	3.8	19.2	61.5	7.7	3.8	3.8	90.7	9.3
JPN	39.4	15.7	7.9	7.9	23.6	5.5	48.6	51.4
KOR	45.0	6.0	25.0	6.0	15.0	3.0	74.1	25.9
MEA	7.7	25.5	38.5	7.7	13.0	7.7	70.1	29.9
RAS	17.6	6.5	60.0	5.9	8.0	2.0	88.7	11.3
RUS	60.0	20.0	5.0	5.0	5.0	5.0	85.4	14.6
SAF	21.6	30.4	21.0	10.0	15.0	2.0	52.7	47.3
SAM	27.5	8.0	38.5	6.0	18.0	2.0	74.0	26.0
USA	44.2	17.7	3.4	6.0	22.4	6.2	56.8	43.2
WEU	60.0	20.0	5.0	5.0	5.0	5.0	82.5	17.6

Source: Adapted from IEA (2011a; 2011b) and IEA (2013)

The categories used were the same as in IEA (2015), which served as basic information for this estimation. They are: Space Heating, Water Heating, Cooking, Lighting, Cooling (Ambient Conditioning) and Appliances.

The energy service intensities, shown in Table 5-25, were calculated relative to the total estimated dwellings. This served as a primary driver for demand calculation, even though there were some adjustments, specific for every service, which will be explained in the next section.

Table 5-25 – Energy service intensity at the base year relative to dwellings

GJ/dwl	Useful Energy					
	Space H	Water H	Cook	Light*	App	Cooling
AFR	6.5	1.4	9.5	0.2	2.6	1.3
AUS	12.8	8.6	1.3	2.2	12.6	1.5
BRA	0.0	0.9	3.8	1.4	3.6	0.3
CAM	0.8	2.5	6.4	1.3	4.0	0.6
CAN	48.2	14.4	2.3	4.0	14.3	2.2
CAS	16.1	2.8	3.4	1.0	2.1	0.4
CHN	7.2	1.7	7.1	0.5	2.0	0.7
EEU	27.8	8.1	1.2	2.7	8.8	1.3
IND	0.6	3.0	5.0	0.4	1.1	1.1
JPN	21.9	8.6	3.0	8.1	17.9	4.2
KOR	20.8	2.9	8.1	5.0	9.3	1.9
MEA	4.1	14.4	14.9	2.7	9.4	5.6
RAS	3.5	1.3	6.2	0.4	3.0	0.7
RUS	50.8	17.4	2.8	2.3	5.1	5.1
SAF	7.3	10.4	5.0	1.8	7.7	1.0
SAM	6.5	2.0	6.0	1.5	6.3	0.7
USA	34.0	14.3	1.9	5.7	23.6	6.5
WEU	25.8	8.8	1.5	1.3	2.8	2.8
World	11.5	4.5	5.6	1.4	5.1	1.6

* Demand in Glmyr/dwl

Just as for the Industrial sector, IEA (2015) was used as a first proxy for energy service composition. However, a few adjustments were made for every region. For instance, the lighting service was assessed in detail, primarily with data from IEA (2006). Table 5-26 presents the estimates for demand and the literature values.

Nonetheless, this table only presents the lighting technology based on electricity. However, several regions of the world still use non-electricity-based technology for lighting, such as kerosene, biomass and candles. The technical and market data for these technologies were compiled from MILLS (2003) and MACHALA (2011).

Several region-specific studies and reports were used to address this topics, such as: Africa (AFR) and South Africa (SAF) (WINKLER, 2006; GELIL, 2011; SOUTH AFRICA, 2012); Middle East (MEA) (GELIL, 2011); USA (DOE, 2012); Canada (CAN) (NRC, 2012); China (CHN) (PNNL, 2012); India (IND) (ELCOMA, 2015; INDIA, 2016; LAM *et al.*, 2016); Rest of Asia and Oceania (RAS) (LAM *et al.*, 2016); Australia (AUS)

(ISAACS *et al.*, 2006); and Brazil (BRA) (LUCENA *et al.*, 2015). Additional global information was taken from IEA (2006) and IIASA (2012).

Achieving adequate household illumination challenges many families in India as well as other developing countries. An estimated 1.2 billion people lacked access to electricity in 2010 (IIASA, 2012), while likely many more experienced frequent supply interruptions. In the absence of electricity, homes frequently turn to fuel-based light sources for illuminating their homes and businesses. Often encouraged by government subsidies, kerosene-fuelled lamps are a common light source.

According to LAM *et al.* (2016), kerosene lamps were used by 380 million in India in 2011 for primary lighting, not including those reliant on it for backup light. The most economically accessible and widely used kerosene lamps provide poor illumination relative to electricity and can be highly inefficient, converting as much as a tenth of the fuel carbon to health-impacting and climate-altering particulate matter (PM). Even after electricity connections are achieved, households may continue to rely on kerosene or other inefficient light sources, such as candles, for some years (LAM *et al.*, 2016).

Table 5-26 – Estimated demand for household lighting across regions

Region	Light Demand (Tlmy)		per capita (Mlmyr/hab)	
	Estimate	Literature	Estimate	Literature
AFR	34	-	0.03	-
AUS	22	24	0.81	0.91
BRA	80	91	0.41	0.49
CAM	65	-	0.33	-
CAN	51	-	1.49	-
CAS	63	-	0.22	-
CHN	200		0.15	0.11
EEU	543	572	0.93	0.98
IND	121	-	0.10	-
JPN	212	241	1.67	1.90
KOR	68	92	1.41	1.90
MEA	160	-	0.74	-
RAS	80	-	0.10	-
RUS	107	145	0.75	1.01
SAF	22	24	0.45	-
SAM	69	-	0.35	-
USA	596	530	1.90	1.69
WEU	34	-	0.41	-
World	2528	2147	0.37	0.31

Source: IEA, 2006; WINKLER, 2006; GELIL, 2011; INDIA, 2016; PROCEL, 2009

India is an interesting case, where opposites happen simultaneously: high participation of off-grid lighting and a relatively higher participation of LED, which has a higher efficiency than average technologies. LAM *et al.* (2016) evaluate the role of kerosene in India's lighting demand. According to the findings, 64% of Indian residential kerosene was consumed for lighting in 2005 (LAM *et al.*, 2016).

The main reasons for the high participation of non-electric technologies for light in India are: subsidies for kerosene consumption in Indian households; share of the population without access to the electrical grid; even in areas with access to the grid, several regions have low supply reliability.

Finally, the estimated participation of non-electric sources of lighting are resented in Figure 5-19.

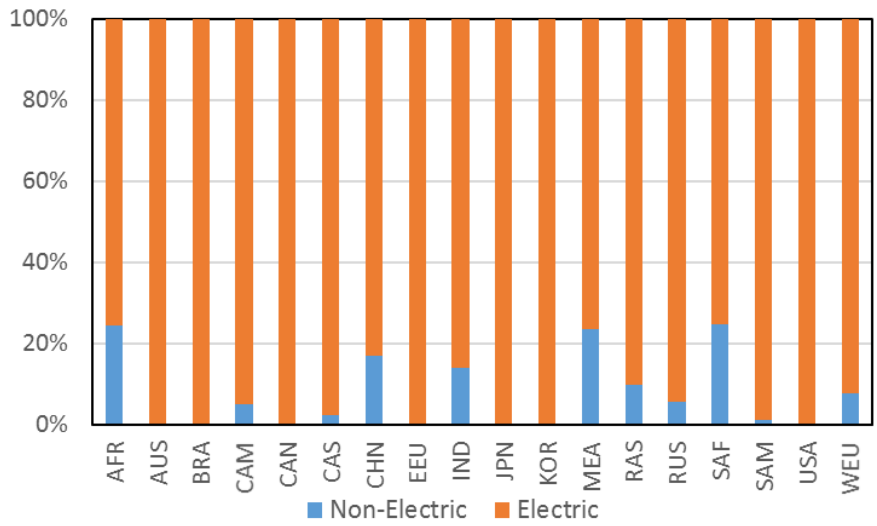


Figure 5-19 – Estimated non-electric lighting demand at base year

5.5.4. Residential Demand

In order to assess the future demand of energy service in the residential sector the intensities mentioned above were used in conjunction with the estimated evolution of dwellings across regions. This was the methodology used for estimating lighting, cooking and water heating demand. However, a few adjustments were made to properly address the remaining energy services.

In order to include the influence of the regional weather on energy service of households, two indicators were used: Heating Degree-Days (HDD) and Cooling Degree-Days (CDD).

HDD are a measure of how much (in degrees), and for how long (in days), outside air temperature was lower than a specific base temperature. They are used for calculations relating to the energy consumption required to heat buildings. On the other hand, CDD are a measure of how much (in degrees), and for how long (in days), outside air temperature was higher than a specific base temperature (DEGREEDAYS, 2016).

They are a measurement designed to measure the demand for energy needed to heating or cooling a building. Degree days are essentially a simplified representation of outside air-temperature data. They are widely used in the energy industry for calculations relating to the effect of outside air temperature on building energy consumption (DEGREEDAYS, 2016).

ATALLAH *et al.* (2015) have compiled a global degree-days database for energy-related applications, including 147 countries. The database was used to estimate the average HDD and CDD for every region, weighted by population of each country. Since the population of every country grow at different rates, the evolution of the HDD and CDD was also estimated, by the following equation:

$$HDD(t) = \sum_{Region} HDD_i \cdot POP_i \Big/ \sum_{Region} POP_i$$

Where $HDD(t)$ is the dynamic HDD of a region, POP is the population and the index i are the countries in a single region. The equation for CDD are equivalent to the equation above.

As such, the energy service intensity estimated in Table 5-25 for ambient heating and ambient cooling were adjusted by the HDD and CDD, respectively. In turn, this adjusted intensity was used to estimate the future demand of space heating and cooling by using the evolution of the HDD/CDD and the number of dwellings. The relationship is described by the following equation:

$$E_{Heat} = f_{Heat} \cdot HDD(t) \cdot N_{Dwellings}$$

Where E_{Heat} is the estimated energy consumption for space heating, f_{Heat} is an adjustment factor specific to each region (e.g. GJ/dwellings/HDD) and $N_{Dwellings}$ is the number of dwellings. Again, the equation for CDD are equivalent to the equation above.

Another service that was tackled with a different methodology was the energy consumption in appliances. In this category all appliances, electronic devices and other equipment are included, such as televisions, computers, laptops, mobile devices, kitchen and cleaning appliances, etc.

This is a complicated service to be assessed in great detail because of several reasons. The main reason is the heterogeneity of services and utilities provided by the equipment in this category, which in turn creates additional difficulty for information availability and common metrics of analysis.

Another important aspect is that consumer behaviour plays a major role in the consumption profile of this particular category. As such, in long term scenario, the expected increase in mean income of a region will have an effect of the consumption profile. This is even more true for low income countries.

In order to assess and include this behaviour in this study, a dependency of the appliances intensity on the HHE is proposed. The estimated appliances intensity presented a strong correlation with the HHE per capita, close to 94%. As such, the appliances intensity for every region increased proportionally to the increase of the HHE per capita. Finally, the total energy service demand was estimated by using the variant intensity and the dwellings estimates.

The estimated evolution in energy service demands for the residential sector is presented in Figure 5-20. As can be seen in this figure, the demand related to appliances presented the highest increase amongst all demands. This is especially true for low income regions, such as Africa (AFR) and Rest of Asia and Oceania (RAS).

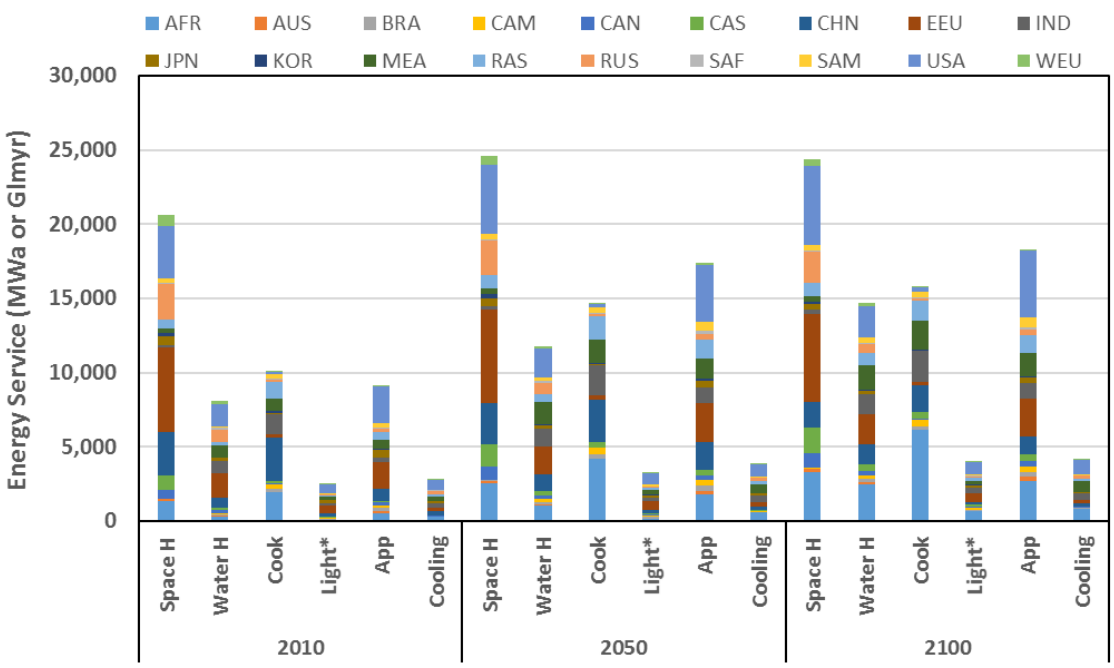


Figure 5-20 – Energy service demand for Households

5.6.Services Sector (excluding transportation sector)

The services sector is the most heterogeneous amongst all sectors assessed in this study. It consists on the tertiary sector of the economy, which is characterized by the production of intangible goods, mostly, rather than products. Included in this sector are commercial activities, government facilities and general services, such as hospitals, restaurants, shopping malls, museums, and companies related to transportation, telecommunication, media, banking, etc.

Out of all the sectors of the economy, the service sector has the lowest average energy intensity. This is due not only to a relative low energy consumption[9], but also to the highest capacity of adding value to the economy. This is way, generally speaking, high income countries present a high participation of the services sector in their GDP, opposed to low income countries, which, again generally, present a higher participation of the agricultural sector.

[9] The energy intensity of the Services sector (excluding transportation) is low in final energy terms, due to the fact that is heavily based on electricity consumption, which is a relatively efficient energy source.

The energy consumption of this sector is directly related to its economic activity. However, just as for industrial and residential sectors, the social structure and welfare, and consumption behaviour are extremely important to determine the consumption profile. Also, other effects, such as weather conditions are considered.

In order to address all these effects systematic and consistently, the approach used in this study is similar to the one used for the residential sector. Though, the driver used for estimating the demand in this sector was not economic production or even buildings, due to the heterogeneity of buildings in this sector. Thus, the driver selected was floor space.

5.6.1. Floor Space

Building floor space for non-residential buildings was estimated in this study. Unfortunately, there are very limited data available for assessing this topic worldwide. The only comprehensive available information found in the literature is found for high income countries, namely the United States (EIA, 1999; EIA, 2003; EIA, 2012) and the European Union (BUILDINGSDATA, 2016).

The available data were compared to the sector GDP per capita, and the findings are presented in Figure 5-21. Just as for the estimation of residential dwellings, the future floor space was estimated from the correlation presented in this figure.

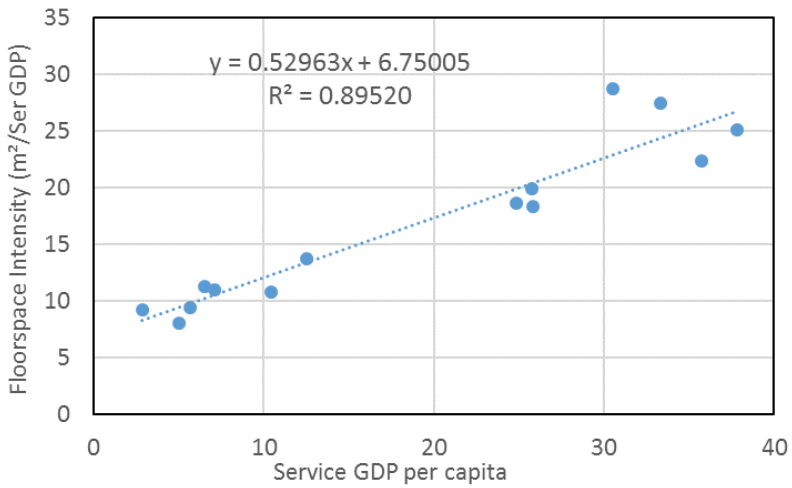


Figure 5-21 – Floor space correlation with GDP per capita

Source: BUILDINGSDATA (2016) and EIA (2012)

It is worth mentioning that this methodology derives only from high income countries data. However, since no available consistent information for other income countries were found, this study, whilst simplistic, provides an unprecedented estimation of buildings for non-residential use.

Finally, using the SSP2 data on population and Service GDP for every region, the total space floor on non-residential buildings were estimated. Figure 5-22 presents the demand for floor space of the services sector.

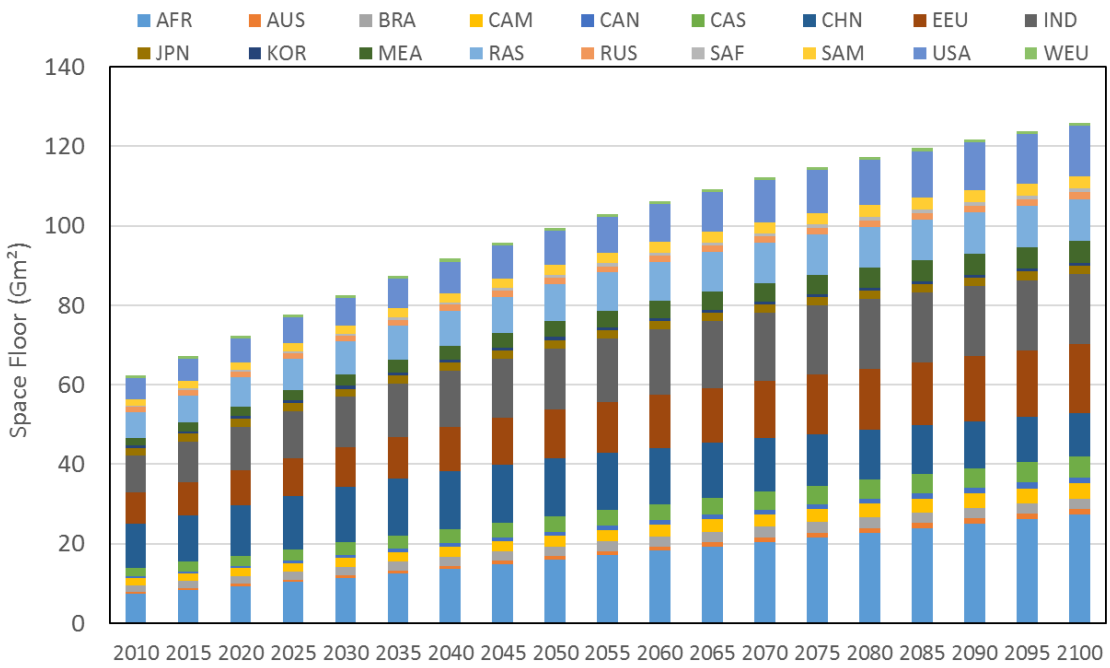


Figure 5-22 – Estimated floor space for service and commercial buildings

5.6.2. Energy Consumption

Just as for the Industrial and Residential sector, the IEA database (IEA, 2011a; IEA, 2011b) was used to estimate the energy consumption in the services sector. The estimated regional consumption, by energy source, is presented in Table 5-27 and Table 5-23. The main energy sources are electricity and natural gas. In terms of total consumption, the most relevant regions are Japan (JPN), Europe (EEU) and United States (USA).

Table 5-27 - Energy consumption for services at base year (PJ)

PJ	Bet. Coal	Sub. Coal	Lignite	NG	LPG	Gasoline	Kerosene	Diesel	Fuel Oil	Biomass	Charcoal	Elect.	Heat
AFR	2.7	0.0	0.0	5.6	7.9	0.2	0.3	39.9	0.3	116.4	6.0	181.3	0.0
AUS	1.5	1.1	1.4	53.1	4.8	0.0	0.3	24.1	0.1	0.6	0.0	234.6	0.0
BRA	0.0	0.0	0.0	7.9	21.3	0.6	0.0	6.5	8.6	5.9	0.8	363.7	0.0
CAM	0.0	0.0	0.0	9.6	63.4	0.0	0.2	8.8	0.5	13.0	0.1	145.5	0.0
CAN	0.0	0.0	0.0	508.7	27.6	0.0	6.3	257.6	49.6	0.2	0.0	519.5	1.9
CAS	2.4	0.0	0.0	426.3	9.0	1.5	1.2	10.2	1.8	1.6	0.0	68.5	1.5
CHN	537.7	0.0	0.0	499.3	74.2	7.5	34.9	746.7	48.9	0.0	0.0	808.0	49.3
EEU	89.7	11.2	10.6	2,078.1	93.7	0.0	1.0	752.6	26.6	84.6	0.1	3,080.2	378.2
IND	208.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	259.0	3.7	218.2	0.0
JPN	22.5	0.0	0.0	720.3	71.2	0.0	302.2	348.1	7.3	0.0	0.0	1,277.7	22.0
KOR	0.0	0.0	0.0	154.6	54.9	2.2	62.0	12.2	11.7	19.1	0.0	494.5	8.1
MEA	0.0	0.0	0.0	223.4	2.3	0.0	4.9	61.1	46.1	0.0	0.0	586.6	0.0
RAS	16.3	0.0	0.0	13.9	93.5	0.0	9.3	76.1	10.9	28.1	1.0	569.3	8.2
RUS	100.3	0.0	21.9	123.4	9.6	1.3	0.0	45.8	11.7	29.8	0.3	556.0	721.0
SAF	96.8	0.0	0.0	0.0	5.1	6.2	1.9	0.0	20.1	0.0	0.0	102.5	0.0
SAM	0.6	0.0	0.0	83.0	14.4	51.4	2.9	16.6	3.2	2.2	0.1	293.9	0.0
USA	54.0	12.6	0.0	3,335.9	50.9	0.2	4.9	437.8	109.6	90.4	4.4	4,764.3	59.7
WEU	8.1	0.2	5.3	29.2	0.1	0.0	0.2	10.1	3.8	10.5	0.1	144.0	56.7

5.6.3. Energy Services

Once again, the energy consumption was disaggregated into energy services categories, such as the ones used in IEA (2015). The categories for the Services sector are the same for the Residential sector. Table 5-28 presents the categories of energy services for every region.

Following the same procedure, from the energy services estimated a set of energy intensities were calculated, as shown in Table 5-29. As mentioned, the intensities were calculated relative to the floor space of non-residential buildings.

Table 5-28 - Services energy consumption separated by energy service (%)

Region	Space H	Water H	Cook	Light	App	Cooling	Fuel	Elect
AFR	43.4	7.7	2.9	18.0	18.0	10.0	49.2	50.8
AUS	22.0	2.0	6.0	16.5	35.5	18.0	27.3	72.7
BRA	3.5	3.0	7.0	33.4	30.0	23.0	12.2	87.8
CAM	16.9	7.0	21.0	20.5	20.0	14.6	39.8	60.2
CAN	61.0	2.0	5.0	12.5	17.5	2.0	62.7	37.3
CAS	61.2	7.0	27.8	1.0	2.0	1.0	86.9	13.1
CHN	39.2	8.0	27.8	7.4	9.7	8.0	67.3	32.7
EEU	46.0	8.0	4.0	11.0	23.0	8.0	52.8	47.2
IND	42.2	5.0	27.8	7.4	9.7	8.0	67.6	32.4
JPN	46.0	8.0	4.0	6.0	29.0	7.0	52.8	47.2
KOR	32.3	7.7	2.9	9.0	33.5	14.6	38.9	61.1
MEA	29.4	7.7	2.9	20.0	22.0	18.0	36.2	63.8
RAS	23.4	7.7	2.9	21.0	23.0	22.0	30.6	69.4
RUS	44.8	0.0	27.8	8.5	14.8	4.0	66.0	34.0
SAF	49.4	7.7	2.9	14.0	18.0	8.0	54.8	45.2
SAM	23.4	7.7	2.9	21.0	23.0	22.0	30.6	69.4
USA	39.0	7.7	2.9	19.6	18.8	12.0	45.1	54.9
WEU	47.1	0.0	2.9	14.0	30.0	6.0	46.3	53.7

Table 5-29 - – Energy service demands intensity at the base year relative to space floor

MJ/m²	Useful Energy					
	Space H	Water H	Cook	Light*	App	Cooling
AFR	14.4	1.9	0.6	16.8	11.0	6.1
AUS	114.2	9.4	21.6	175.9	247.4	125.5
BRA	6.0	4.5	8.0	117.8	71.1	54.6
CAM	17.9	7.3	15.7	44.2	29.4	21.5
CAN	1047.3	29.3	58.1	451.4	400.5	45.7
CAS	112.9	13.7	37.1	3.7	4.8	2.4
CHN	75.2	12.5	37.2	27.0	27.0	22.2
EEU	246.1	45.3	14.7	120.0	164.0	57.0
IND	20.3	1.5	6.7	10.0	7.9	6.5
JPN	416.9	59.4	24.2	143.4	352.5	85.1
KOR	299.6	65.9	18.5	222.5	421.7	183.5
MEA	132.0	30.0	8.9	182.6	131.3	107.4
RAS	23.3	6.4	1.9	45.3	32.4	31.0
RUS	445.7	0.0	166.9	162.2	182.9	49.3
SAF	196.9	19.8	8.2	134.0	112.7	50.0
SAM	48.5	17.2	4.2	85.4	63.9	61.1
USA	412.0	81.5	22.2	436.4	264.5	168.9
WEU	138.3	0.0	5.3	84.6	118.6	23.7
World	141.5	22.4	19.1	99.7	93.6	46.8

* Demand in Glmyr/m²

A specific analysis was made for estimating lighting demand for the services sector. IEA (2006) provides very useful and detailed information on global demand and selected countries profiles. Several other reports and studies were used to improve the overall estimate, as presented in Table 5-30.

Table 5-30 - Estimated demand for services lighting across regions

Region	Lighting Demand (Tlmy)	
	Estimate	Literature
AFR	124	-
AUS	81	73
BRA	206	210
CAM	79	-
CAN	271	274
CAS	8	-
CHN	299	287
EEU	1065	1296
IND	93	-
JPN	327	374
KOR	145	140
MEA	352	-
RAS	294	-
RUS	213	216
SAF	61	-
SAM	141	-
USA	2664	2026
WEU	57	111
World	6480	7392

Source: IEA, 2006; WINKLER, 2006; GELIL, 2011; INDIA, 2016; PROCEL, 2009

5.6.4. Service Demands

The assessment of the future demand for energy services in the services sector was based on the intensities mentioned previously. They were used in conjunction with the estimated evolution of the floor space across regions. This was the approach used for estimating lighting, cooking and water heating demand.

Nevertheless, just as for the residential sector, a few adjustments were made to properly address the remaining energy services. Specifically, for ambient heating and cooling, the database available in ATALLAH *et al.* (2015) was used to estimate the average HDD and CDD for every region.

As such, the energy service intensity estimated in Table 5-29 for ambient heating and ambient cooling was adjusted by the HDD and CDD, respectively. In turn, this adjusted intensity was used to estimate the future demand of space heating and cooling by using the evolution of the HDD/CDD and the future floor space in non-residential buildings. The methodology used is the same as the one used for the Residential sector.

Another service that was tackled with a different methodology was the energy consumption in appliances. Just like in the residential sector, this category includes all appliances, electronic devices and other equipment. However, one would expect that computer, printers and other electronic devices are generally more relevant than cleaning and kitchen appliances.

In order to assess the evolution of the energy intensity of appliances in the service sector, a dependency function of the appliances intensity on to the Service GDP is proposed. The estimated appliances intensity presented a relatively high correlation with the Service GDP per capita, close to 85%. As such, the appliances intensity for every region increased proportionally to the increase of the Service GDP per capita. Finally, the total energy service demand was estimated by using the intensity and the floor space estimates.

The estimated evolution in energy service demands for the services sector is presented by Figure 5-23. As can be seen, the demand related to appliances presented the highest increase amongst all demands. This is especially true for low income regions, such as Africa (AFR) and Rest of Asia and Oceania (RAS).

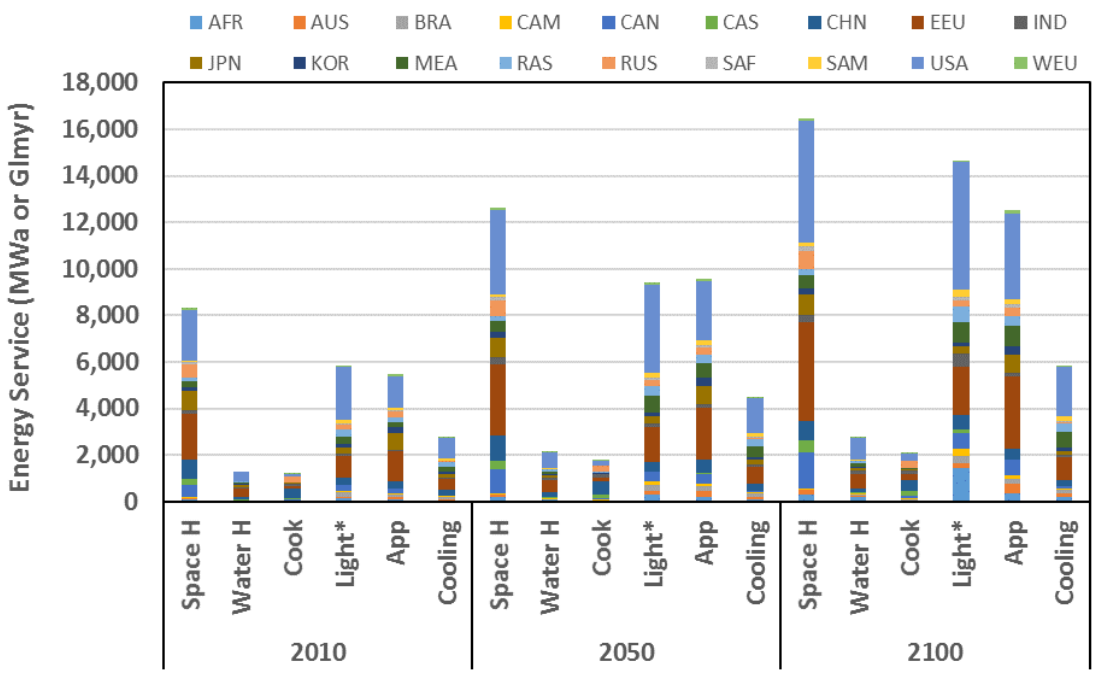


Figure 5-23 - Energy service demand for Services

5.7.Residues Sector

The last sector assessed in this chapter presents a characteristic behaviour. The main difference is that, unlike the previous sectors, the emissions related to the residue sector are not associated with energy consumption or industrial processes, but are due to the decomposition of organic matter within the residues.

Just like the tertiary sector, this sector provides a service to society and does not involve the production of an end product. However, since the environmental service provided by collecting and treating residues is not properly valued by society, being relatively less significant in the value added to the economy than other activities of the services sector.

Generally speaking, the residue sector is not a major source of GHG emissions. However, there are two reasons to address this sector in detail. First of all, there are a few abatement options, which can also provide further co-benefits to society, such as reduction of environmental damages. Other advantage is that some options of treatment can also provide alternative source of energy (waste-to-energy options).

The other reason is that the GHGs typically emitted by this sector are methane and nitrous oxide, which, even if emitted in low quantities, have a higher impact on the greenhouse gas effect. Hence, changes in consumption behaviour and the development of collecting and treatment options within all regions may prove to be an important source of GHG emissions.

There are a few sources of emissions within the residue sector, such as municipal solid waste (MSW), liquid effluents and agricultural residues. The latter will be addressed in the next chapter. As for liquid effluents, there is very limited literature for assessing this topic worldwide. As such, the only source of emissions in this sector addressed by this section is MSW.

5.7.1. MSW production and destination profile

Currently, world cities generate about 1.3 billion tonnes of solid waste per year. This volume is expected to increase to 2.2 billion tonnes by 2025. Waste generation rates will more than double over the next twenty years in lower income countries (WB, 2012).

A report made by the World Bank (WB, 2012) provides a quick snapshot of the state of today's global solid waste management practices. Also, an estimate is made for what the situation will look like in 2025. This report was the most relevant source of information regarding MSW found in the literature, due to the standardization of data and regional representation, including 161 countries from all 18 regions of the model.

The first important information is the estimated production rate of MSW per country, which was compiled for every region, as shown in Table 5-31. The table also presents another major aspect of MSW, which is the collection rate of the generated MSW to treatment options and final destinations. Relatively speaking, despite all regions present a high collection rate, ideally the rate should be very close to 100%, in order to avoid environmental damage, health hazards and minimize GHG emissions.

Table 5-31 – MSW generation and collection rate

	MSW Ger. kg/hab/day	Collection (%)
AFR	0.681	0.800
AUS	2.492	0.960
BRA	1.032	0.830
CAM	1.258	0.840
CAN	2.331	0.990
CAS	0.870	0.651
CHN	1.031	1.000
EEU	1.871	0.960
IND	0.341	0.822
JPN	1.713	1.000
KOR	1.244	0.990
MEA	0.886	0.867
RAS	0.778	0.822
RUS	0.931	0.867
SAF	1.999	0.867
SAM	1.018	0.866
USA	2.582	1.000
WEU	0.727	0.867

Source: Adapted from WB, 2012

As for the MSW that are indeed collected, there are several disposal methods, each with their own characteristics, emission profile and costs. In this study the disposal options are separated into six categories: dumps; landfills; compost; recycling; waste-to-energy facilities; and incineration. For more information on the disposal methods, see UNEP (2005); WB (2012); GDRC (2016) and IPCC (2006).

Table 5-32 – MSW disposal method by region (%)

	Dumps	Landfills	Compost	Recycled	W2Ene	Incin
AFR	81.3	14.4	0.6	3.1	0.0	0.7
AUS	0.0	73.8	0.0	26.2	0.0	0.0
BRA	38.9	45.6	0.0	0.0	0.0	15.5
CAM	3.1	82.9	0.6	2.5	0.0	11.0
CAN	0.0	0.0	12.5	26.8	0.0	60.7
CAS	0.0	100.0	0.0	0.0	0.0	0.0
CHN	0.0	53.4	0.0	42.9	0.0	3.7
EEU	10.4	48.1	15.5	10.9	9.8	5.3
IND	0.0	2.3	0.0	19.1	0.0	78.6
JPN	0.0	3.0	0.0	17.0	74.0	6.0
KOR	0.0	36.0	0.0	49.0	14.0	1.0
MEA	26.5	58.0	3.0	10.5	0.0	2.0
RAS	0.0	2.3	0.0	19.1	0.0	78.6
RUS	0.0	92.8	3.6	0.3	0.0	3.2
SAF	26.5	58.0	3.0	10.5	0.0	2.0
SAM	38.9	45.6	0.0	0.0	0.0	15.5
USA	0.0	54.0	8.0	24.0	14.0	0.0
WEU	0.0	92.8	3.6	0.3	0.0	3.2

Source: Adapted from WB, 2012

Table 5-32 presents the estimated distribution of disposal methods of all collected MSW, for every region. However, the disposal method alone is not enough to estimate the GHG emission profile due to MSW.

As presented in IPCC (2006), the composition of the MSW is extremely important in order to assess the potential GHG emission of the MSW. The composition of the MSW varies widely across regions, as shown in Table 5-33. It is directly related to the consumption behaviour, socioeconomic factors, such as income and education, as well as cultural aspects.

Using the methodology presented in IPCC (2006), the potential emissions factor of CH_4 per tonne of MSW was estimated. This value, also shown in Table 5-33, is directly

related to the MSW composition. Thus, the potential emissions and eventual abatement potential of this sector will be related to this emission factor, the disposal method and the generation of MSW by every region.

Table 5-33 – MSW composition for every region (%)

	Organic	Paper	Plastic	Glass	Metal	Other	DOC	L0	tCH_4/t_{MSW}
AFR	61.0	10.7	10.0	3.1	1.2	14.0	16.1	8.2	0.074
AUS	49.4	22.5	5.1	5.9	3.7	13.5	18.7	9.6	0.087
BRA	61.0	15.0	15.0	3.0	2.0	4.0	16.8	8.6	0.077
CAM	50.0	15.7	9.0	5.5	3.0	16.7	16.5	8.5	0.076
CAN	24.0	47.0	3.0	6.0	13.0	7.0	23.6	12.1	0.109
CAS	64.7	7.2	16.8	2.2	0.5	8.7	14.7	7.6	0.068
CHN	36.4	25.0	19.2	3.0	2.0	14.4	17.6	9.0	0.081
EEU	31.2	24.6	12.2	9.1	3.7	19.2	17.1	8.8	0.079
IND	35.0	3.0	2.0	1.0	0.0	59.0	13.1	6.7	0.060
JPN	26.0	46.0	9.0	7.0	8.0	4.0	23.2	11.9	0.107
KOR	28.0	24.0	8.0	5.0	7.0	28.0	17.2	8.8	0.079
MEA	53.3	17.4	12.0	3.2	2.5	11.5	17.2	8.8	0.079
RAS	57.5	9.7	12.0	5.3	4.9	10.6	14.7	7.5	0.068
RUS	23.6	27.7	10.6	10.1	5.6	22.4	17.3	8.9	0.080
SAF	53.3	17.4	12.0	3.2	2.5	11.5	17.2	8.8	0.079
SAM	47.6	16.4	10.5	4.2	2.0	19.4	16.6	8.5	0.077
USA	25.0	34.0	12.0	5.0	8.0	16.0	19.5	10.0	0.090
WEU	23.6	27.7	10.6	10.1	5.6	22.4	17.3	8.9	0.080

Source: Adapted from WB, 2012

In order to understand the abatement options, the optimization model requires technical parameters, such as investments and additional costs, to promote a competition between the technologies. The data used in this analysis are based on EUNOMIA (2001), which provides a dataset of prices and costs of waste management options, which were used to undertake an economic analysis.

Table 5-34 – Cost of MSW disposal methods

Data	Unit	Compost	Incineration	Landfill	WTE	Dump	Recycled
Investment	US$/Mt	199.7	609.6	125.1	150.1	93.8	46.9
Fixed O&M	US$/Mt	8.2	38.5	11.0	11.5	5.5	11.0
Plant Life	years	30	50	50	50	50	50
Const. Time	years	5	5	10	10	2	2

Source: Adapted from EUNOMIA, 2001

5.7.2. Evolution of MSW generation

In order to estimate the GHG emissions of this sector and the potential reduction in climate constrained scenarios, the evolution of MSW was assessed. As mentioned previously, WB (2012) claims that MSW generation will likely increase in the near future, with a strong increase in lower income countries.

To incorporate this issue into the methodology, a correlation between the MSW generation rate and the HHE per capita was proposed. The findings are presented in Figure 5-24, and show a clear increase in MSW production when income level increases.

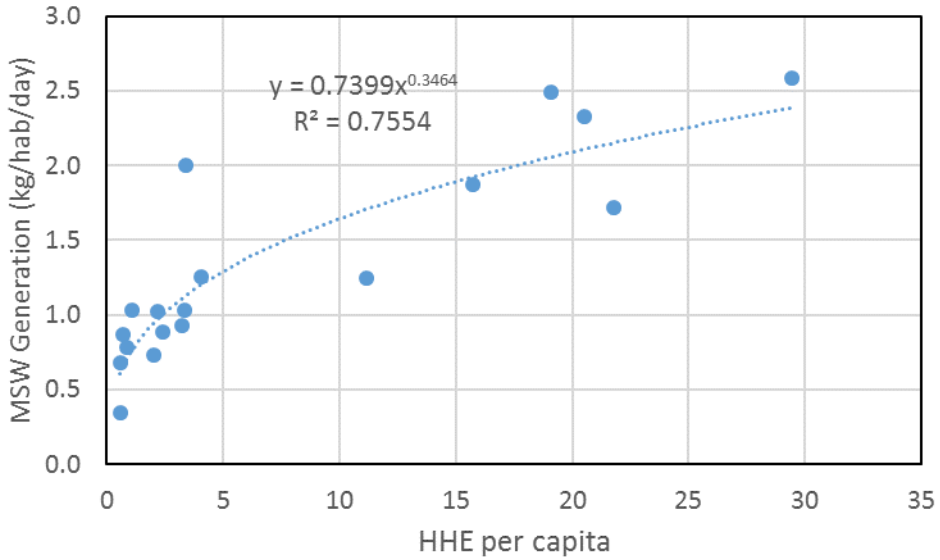


Figure 5-24 – MSW generation profile correlation with HHE per capita

Legend: HHE - Household Expenditure

The estimates performed in WB (2012) until 2025 were also taken into account when projecting the trend for MSW production until 2100. The results are shown in Figure 5-25. The findings depend on the evolution of the HHE per capita, which affect the MSW generation rate, and the population size of every region.

Despite accounting for an increase in production of MSW when income levels grow, an assessment to affect the composition of the MSW was not performed by this study. As such, the profile presented in Table 5-33 was kept constant throughout the time period.

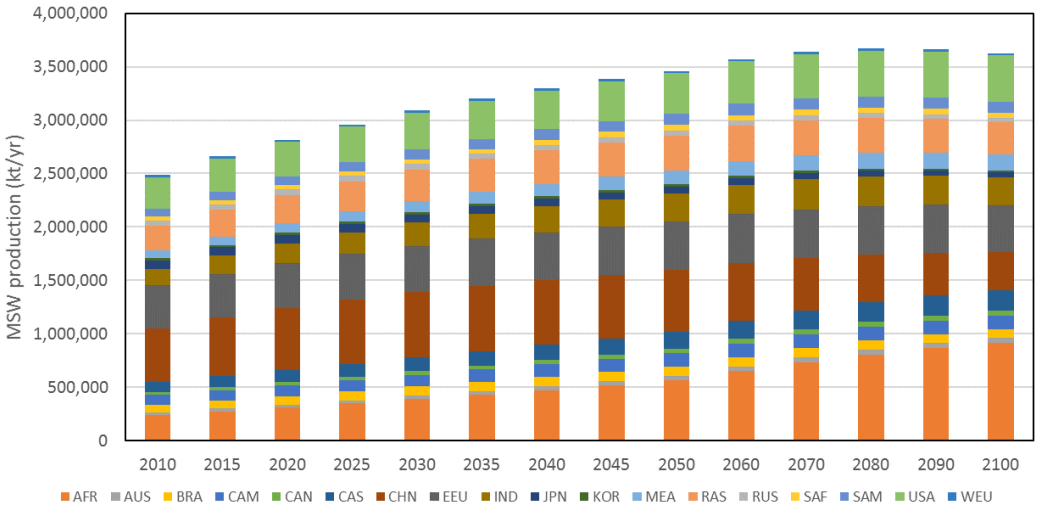


Figure 5-25 – MSW production for all regions

It is important to emphasize that the assessment of MSW in this study, whilst important and not commonly addressed in some IAMs (such as IIASA's MESSAGE), is rather simplified and could be enhanced in future studies. For instance, not all abatement options were fully assessed, such as changes in consumption behaviour and enhancing reuse and reduction of MSW. Also, a more detailed analysis on GHG emissions of disposal methods and the potential and costs of abatement options could improve the representation of this sector within the model.

5.8. Agriculture Sector

The agriculture sector and its energy-related emissions will be addressed in the next chapter, together with the non-energy related emissions of this sector, the land use, land use change and forestry emissions.

6. Agriculture and Land

This chapter describes in simple terms the complex behaviour of the land systems and, more specifically, the dynamic relationship between the land and the energy systems. According to IPCC (2014), the AFOLU system was responsible for close to a quarter of total GHG emissions in 2010.

This is the first main reason why properly addressing the land systems within a modelling framework devoted to assessing GHG emissions is of extreme importance. Thus, all the sectors presented in the previous chapters (energy production and consumption, industrial processes and residues) are responsible for about 75% of global GHG emissions.

Additionally, another major reason for addressing the land system is the importance of this system in economic terms. As mentioned in the previous chapter, agriculture is one of the main activities of the economy. It is a sector which provides basic goods mostly related to, but not exclusively, food supply. Thus, due to the importance of the service provided by this sector to society, the economic activity of agriculture is expected to maintain its relative importance in the GDP in the SSP2 scenario.

The relationship between the land and the energy systems is another major issue that needs to be addressed in IAM frameworks. This becomes even more important when considering future scenarios that concern limiting long term climate change, mostly given the potential role of bioenergy in making the achievement of such objective possible (AZAR *et al*., 2010; KRIEGLER *et al*., 2014; DAIOGLOU, 2016).

According to IEA (2015), bioenergy was responsible for a little over 10% of total primary energy consumption globally in 2013. Bioenergy comes in all shapes and forms, meaning that it can be used as solid fuels (e.g. traditional biomass), as gaseous fuels (e.g. biogas) and as liquid fuels, such as ethanol and biodiesel.

The latter is amongst the most important uses of biomass as an energy feedstock, which enables the transportation sector to reduce carbon emissions. For instance, biofuel blending mandates are now in place in around 60 countries (IEA, 2015). Furthermore, advanced biofuels are expected have a major role in long-term climate constrained scenarios (EMF, 2016).

CCS and bioenergy, and in particular the combination of both (BECCS), play a crucial role in compensating the direct emissions from the end use sectors by making negative emissions possible. Thus, BECCS notably affects the cost effective global

emissions trajectory by accommodating prolonged use of fossil fuels without CCS. It should be noted that many models lack representation of alternative negative emissions technologies such as afforestation (KRIEGLER *et al.*, 2014)

According to AZAR *et al.* (2010), including BECCS in a modelling framework allows for much lower targets to become attainable—and also at lower costs. In contrast, for less ambitious targets, including BECCS into the technology portfolio has hardly or even no influence on costs. This implies that BECCS (and, for that matter, CCS) can be considered, at this moment, a pivotal technology in attaining low stabilisation targets (AZAR *et al*., 2010).

6.1.Land categories

IAMs have been used to investigate the effect of different scenarios on the supply of biomass and the dynamics of the land system (DAIOGLOU, 2016). The scenarios account for different demands for food, feed, fibres and bioenergy, with regards to different technological, economic and environmental constrains.

Several IAMs use geographically explicit models for assessing land systems, such as MAGPIE, IMAGE and GLOBIOM. In this type of model, the potential distribution of natural vegetation and crops is determined on the basis of climate conditions and soil characteristics with spatially explicit biophysical inputs such as land, agricultural yields and water availability (IIASA, 2015).

These models are amongst the most elaborate global land models in the world. As such, the complexity of the relationships, the amount of data needed and the computational effort involved in developing such a model are overwhelming, and as such beyond the scope of this study.

Nevertheless, there are other approaches used in IAMs to address the land system that are non- “spatial explicit”. Even though this is a limited approach to dealing with a highly complex system, it provides good insights and can have a good representation of global systems (EMF, 2016).

Some models use agro-ecological zones (AEZ) to enhance regional representation. For instance, GCAM, which originally presented 14 geo-political regions, has 151 land regions with different parameters, such as crop yields and carbon stock (KYLE *et al*., 2011; WISE *et al*., 2014).

Another example of global IAM that uses AEZ is the AIM-CGE. This model, however, has a land nesting strategy, where land is one of the production factors available for production functions. AIM uses 18 AEZ, which are basically land cover types for every region (WINNING, 2013).

Thus, the approach used in this study was to develop a non- "spatial explicit" model into the MESSAGE framework, with the object of optimizing land use in order to meet demand for food and bioenergy products. The methodology is a little different than the ones presented earlier, but it is believed to be an adequate representation of the land system at this time.

In order to create the land categories, or zones, several aspects must be considered, such as land cover, yields, soil productivity and estimates for production costs. These aspects will be addressed in the following sections, with the objective of creating a supply curve for biomass.

6.1.1. Land Cover

The most basic aspect of the land systems is the land cover. The definition of land cover is fundamental, because in many existing classifications and legends it is confused with land use. It is defined by FAO (2000) as "Land cover is the observed (bio)physical cover on the earth's surface".

Land cover data document how much of a region is covered by forests, wetlands, impervious surfaces, agriculture, and other land and water types. Water types include wetlands or open water, which can be determined by analysing satellite and aerial imagery (NOAA, 2016). Land use shows how people use the landscape – whether for development, conservation, or mixed uses and, as such, land use cannot be determined from satellite imagery (NOAA, 2016).

The land cover categories considered in this study are based on UNEP (2015) and are presented in Figure 6-1. The figure presents the global map for land cover with a spatial resolution of 300 m x 300 m, or a grid cell size of 9 hectares. For land use and agriculture assessments, the most important land covers are: cropland, which are used for agricultural production; forests, which could be protected or not; and grasslands, which includes savannahs and natural vegetation.

It is important to note that the category “Not Suited” is regional exclusions for agricultural productions and eventual land use changes. It basically considers desert areas, permanent ice sheets and human-made built areas.

6.1.1. Soil productivity

The second aspect introduced in this analysis is related to relative soil productivity. The Productivity Index (PI) is an ordinal measure of the productivity of a soil. The PI uses family-level Soil Taxonomy information, i.e., interpretations of taxonomic features or properties that tend to be associated with low or high soil productivity (SCHAETZL *et al*., 2012).

The index has wide application because, unlike competing indexes, it does not require copious amounts of soil data, e.g., pH, organic matter, or CEC, in its derivation. GIS applications of the PI, in particular, have great potential. For regionally extensive applications, the PI may be as useful and robust as other productivity indexes that have much more exacting data requirements (SCHAETZL *et al*., 2012).

The raster dataset of soil production index used in this study has a spatial resolution of 5 * 5 arc minutes[10] and is in geographic projection. Information with regard to soil production was obtained from the "Derived Soil Properties" of the FAO-UNESCO Soil Map of the World which contains raster information on soil properties (FAO, 2016). The soil production index considers the suitability of the best adapted crop to each soil’s condition in an area and makes a weighted average for all soils present in a pixel (NACHTERGAELE, 2003)

The Index, represented in the map in Figure 6-2, ranges from 0% to 100% and was used as a proxy for productivity and relative yield between land categories. The average yields for every crop and region were taken from FAO (2015) and will be further discussed later.

Once again, it is worth pointing out that the methodology used in this study has some limitations, and the use of the soil productivity index is perhaps the most controversial aspect of the land systems assessment methodology used in this study. The reason this index was used as a proxy for relative productivity is that it relies in very few

[10] Equivalent to 10 km grid cells.

additional information. However, the simplicity is exactly what creates the limitations of this analysis, since it disregards other aspects, such as water availability and climatic conditions which limit crop production.

6.1.1. Travel Time

Additionally, another aspect used to enhance the analysis was an estimation of production costs. Production costs of agricultural products were differentiated by soil productivity and, therefore, by yield. However, another important aspect related to costs is the transportation cost of agricultural goods. This is a limiting factor in exploring certain areas for increasing agricultural production.

In this category, UNEP (2015) and ESA (2008) present a georeferenced map for estimating travel time of a pixel into the nearest major city. The map shows how accessible some parts of the world have become whilst other regions have remained isolated (ESA, 2008). Figure 6-3 presents a compiled version of the data from ESA (2008). As such, travel time was used as a proxy for distance, which, in turn, was used as a proxy for transportation costs.

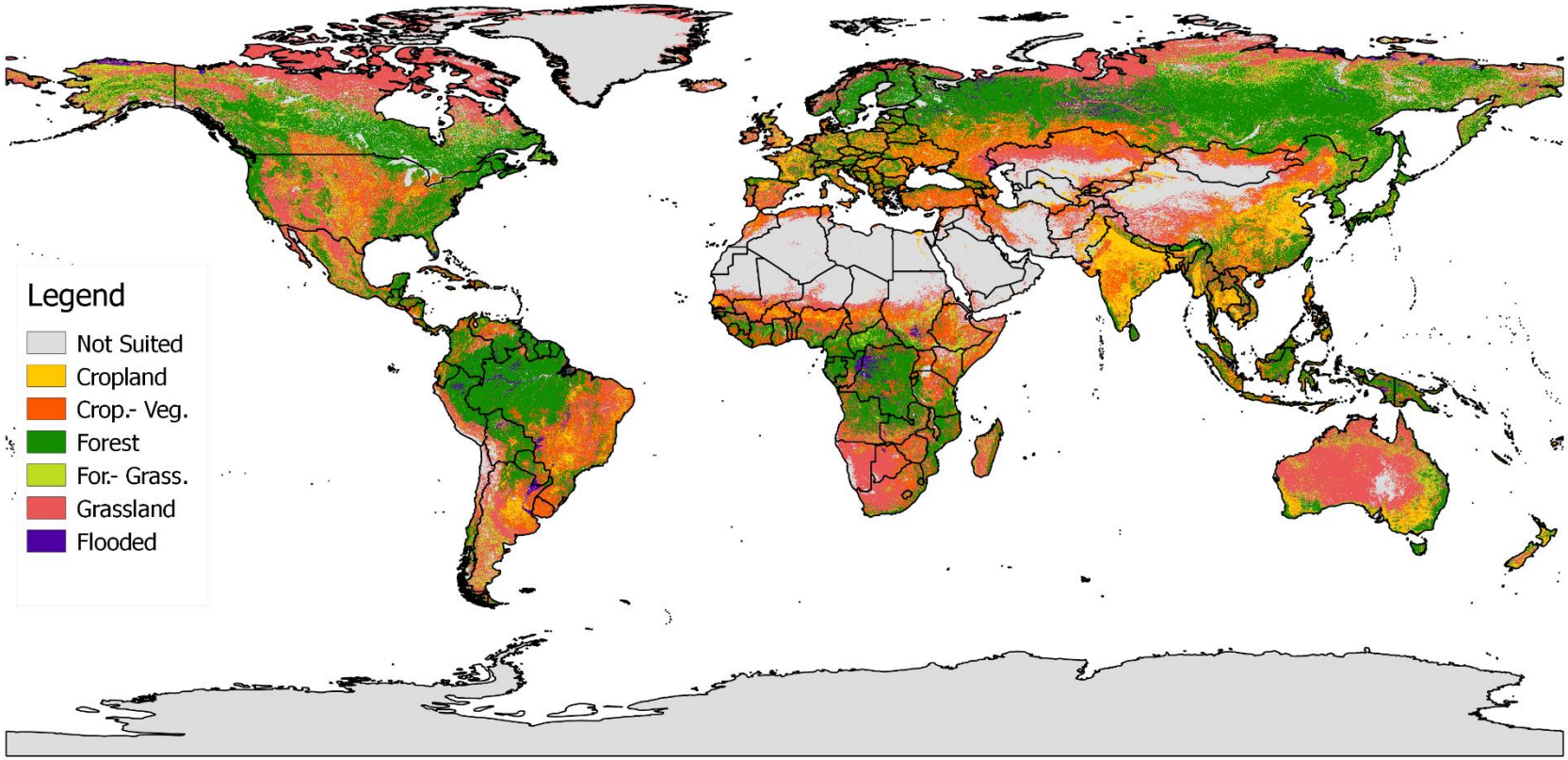


Figure 6-1 – Land cover categories

Source: Adapted from UNEP, 2015

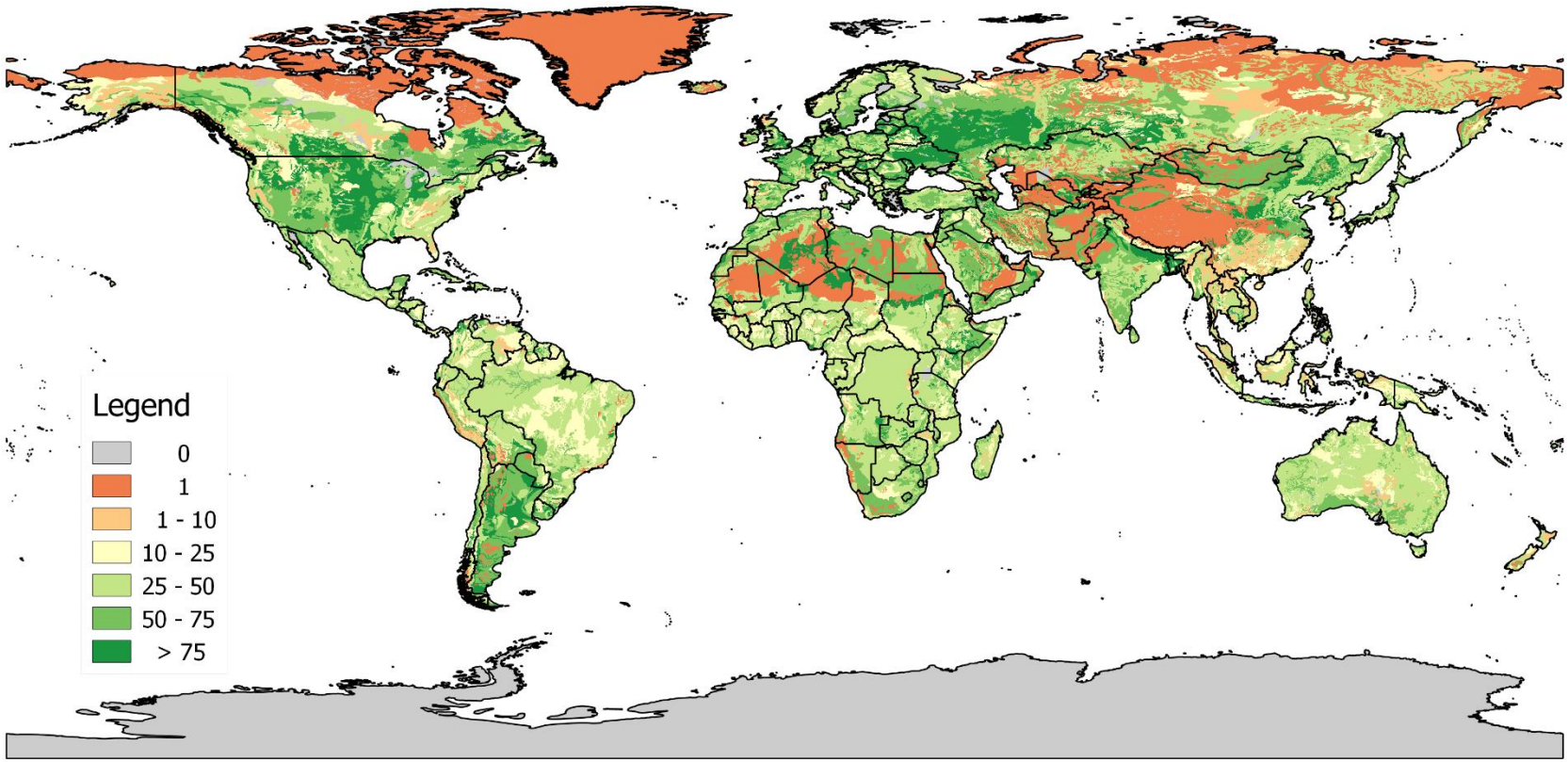


Figure 6-2 – Soil productivity categories (index in %)

Source: Adapted from UNEP, 2015

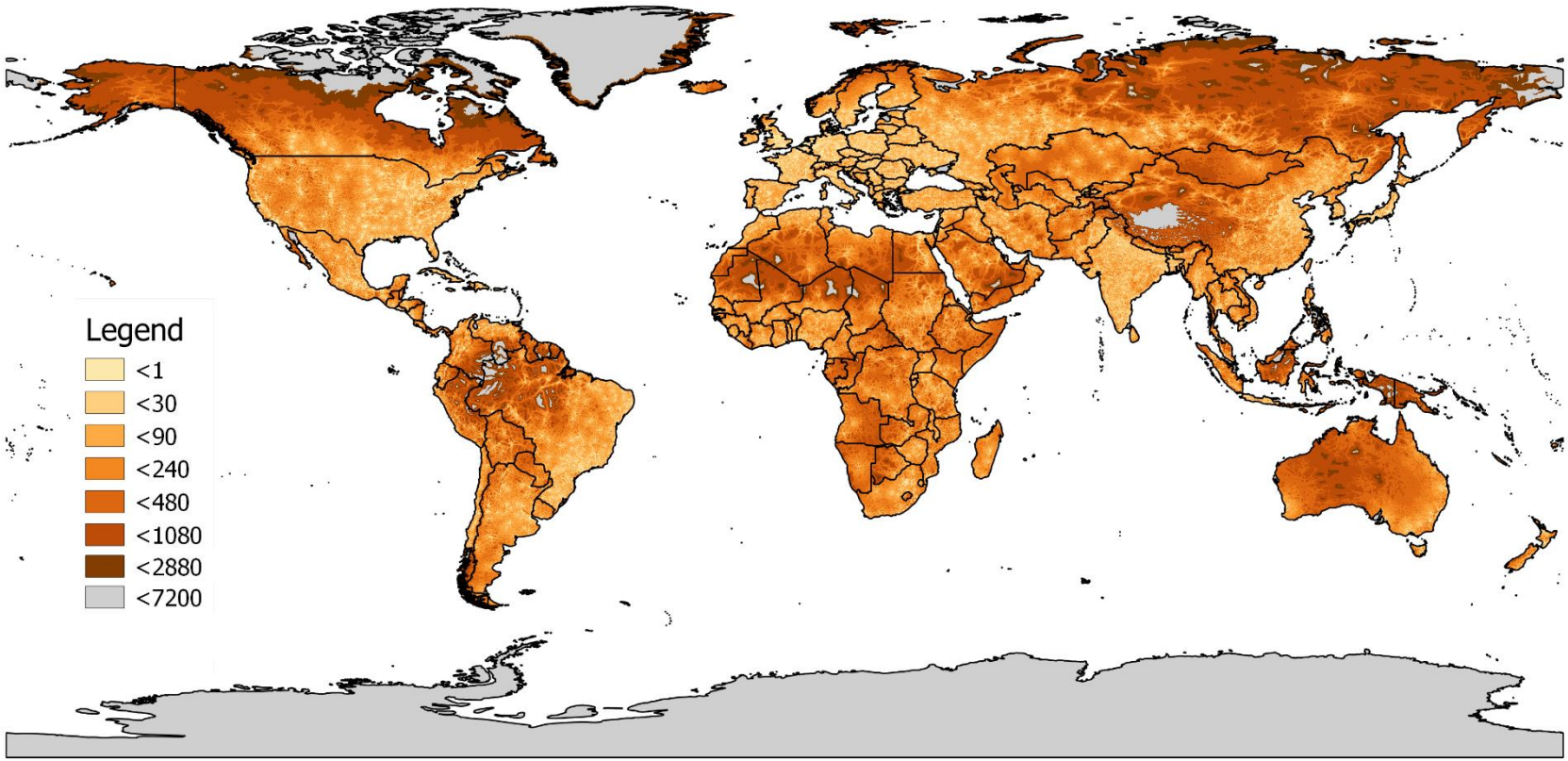


Figure 6-3 – Travel time categories (in hours)

Source: Adapted from UNEP, 2015

6.1.2. Aggregated categories

All three land aspects were aggregated in Quantum GIS, a free and open-source platform for geographic information systems (GIS). The first issue that arises in doing this aggregation is the different spatial resolution used by each category. The grid sizes are presented in Table 6-1. The land cover map has the smallest grid, which means the highest resolution. On the other hand, soil productivity has a resolution almost one thousandth of that.

Table 6-1 – Grid size and area for the three land aspects

Category	Length (m)	Area (km²)	Area (ha)
Land Use	300	0.09	9
Soil Prod.	9300	86.49	8649
Travel Time	930	0.86	86

Therefore, the first part of combining all land aspects in one raster was to disaggregate the lower resolutions files to adjust them into the higher resolution grid. This was done by maintaining the original values of a large area for every pixel. For instance, every Travel Time cell was expanded into almost 10 cells equivalent to the cell size of the Land Cover. Thus, for all the new cells, the value of the original large cell was used. As such, a combined raster with the highest resolution was created.

Then, the second step of the process involved re-aggregating cells into fewer categories, to be used within MESSAGE. The land cover was not modified and all original types were kept.

Thus, 8 land cover types were considered. However, the “Not Suited” category, as the name suggests, was not considered for assessing agricultural production and potential land use change.

So, the re-aggregation was based on production costs and the categories which could be related to production costs: soil productivity, which accounts for relative production costs at the field, and travel time, which accounts for relative costs of transportation. Ergo, the influence of both categories of production costs was combined in this assessment, creating a step function for production cost.

As for the productivity, the highest value of the range of each step shown in Figure 6-2 was used as a proxy for yield and, therefore, inversely proportional to costs. For

instance, for the category that ranges between 50% and 75%, the 75% value was used as a proxy. Thus, relative production costs were considered to be 1.33 times higher compared to the cost of a cell with 100% productivity.

On the other hand, for the transportation costs, the technology and transportation mode used depend primarily on the distance. The effects of transportation infrastructure were not considered in this assessment. Thus, three transportation options were considered: trucks, for distances up to 1.000 km; trains, for distances between 50 km and 2.000 km; and ships, for distances larger than 200 km.

Each technology is associated with a cost curve relating to distance, such as the one presented in HOFFMANN (2013) for transportation of biomass by trucks. The parameters for rail transportation costs were taken from LIN *et al*. (2013), and the ship technical and economical parameters were taken from VESSELDISTANCE (2015). The latter allows you to select not only the course, but also between a range of vessels and their default parameters, such as cruise speed and fuel consumption.

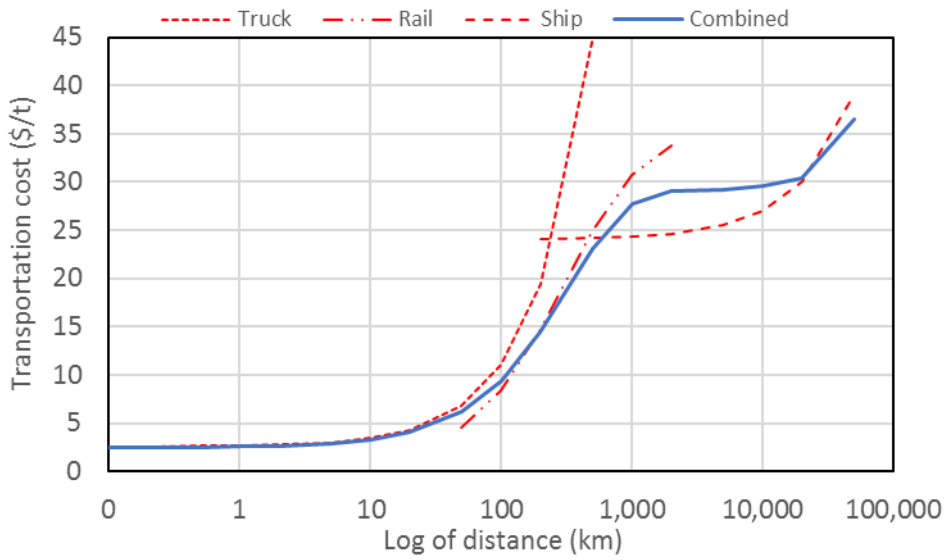


Figure 6-4 – Estimated transportation cost of biomass

Source: based on data from HOFFMAN (2013), VESSELDISTANCE (2015) and LIN *et al.* (2015)

All three cost curves estimated from the literature are presented in Figure 6-4. The same figure presents the combined cost curve for all three options. Whenever two technologies overlap, the average cost was considered. As can be seen, the relationship is non linear and has a very eccentric mathematical behaviour.

Thus, two factors were considered to estimate relative production costs: productivity and transportation. So, by combining all categories of Soil Productivity and Travel Time, a matrix of relative costs for 56 cells was designed. The findings are presented in Table 6-2. The relative production costs regarding transportation are presented horizontally, and productivity, vertically.

The colour scheme in Table 6-2 presents the proposed aggregation of relative production costs for all options. In total, the 56 cells were aggregated in 7 new cost categories. However, the seventh category, with costs higher than 100, was not considered as viable for agricultural production.

Table 6-2 – Relative costs and aggregated categories between Soil production and Travel

		Travel Time (h)							
		1	30	90	240	480	1080	2880	7200
Soil Production	1%	20.0	53.1	79.4	84.9	85.5	88.9	115.5	144.3
	5%	10.0	26.6	39.7	42.5	42.7	44.4	57.8	72.2
	10%	4.0	10.6	15.9	17.0	17.1	17.8	23.1	28.9
	25%	3.3	8.9	13.2	14.2	14.2	14.8	19.3	24.1
	50%	2.0	5.3	7.9	8.5	8.5	8.9	11.6	14.4
	75%	1.3	3.5	5.3	5.7	5.7	5.9	7.7	9.6
	100%	1.0	2.7	4.0	4.2	4.3	4.4	5.8	7.2

LEGEND: A B C D E F

Finally, for every one of the 18 regions a two-factor land system was created, considering 7 land cover types and 7 combined cost categories. Figure 6-5 and Figure 6-6 presents the main findings of the analysis for the land system.

This methodology allows the assessment of the land use and land use change, whilst considering economic aspects. Thus, a supply curve for agricultural products, including bioenergy, is available within the model.

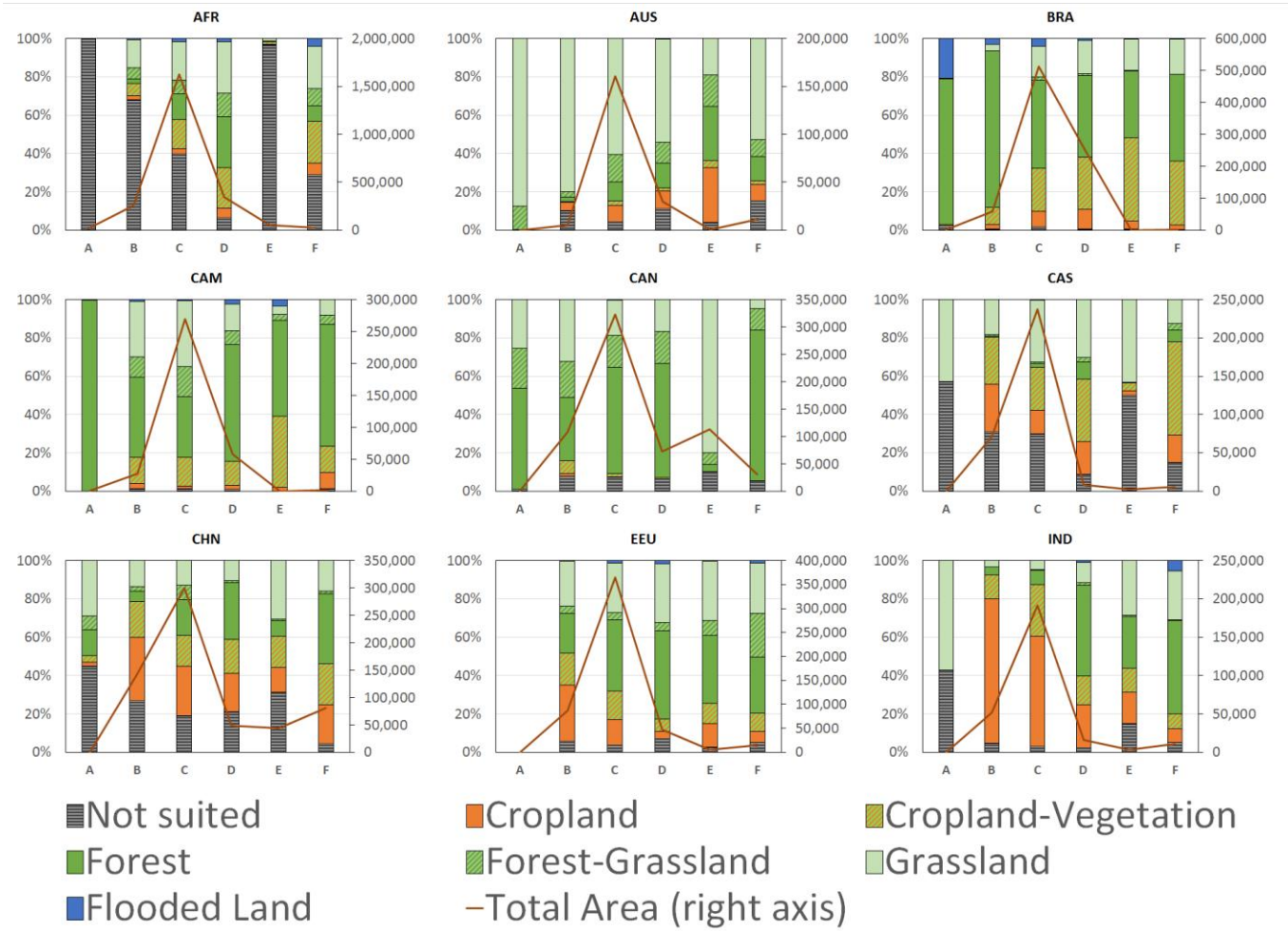


Figure 6-5 – Aggregated land use and categories for all regions (part 1)

Legend: Land categories in % (left axis) and area in k hectares (right axis)

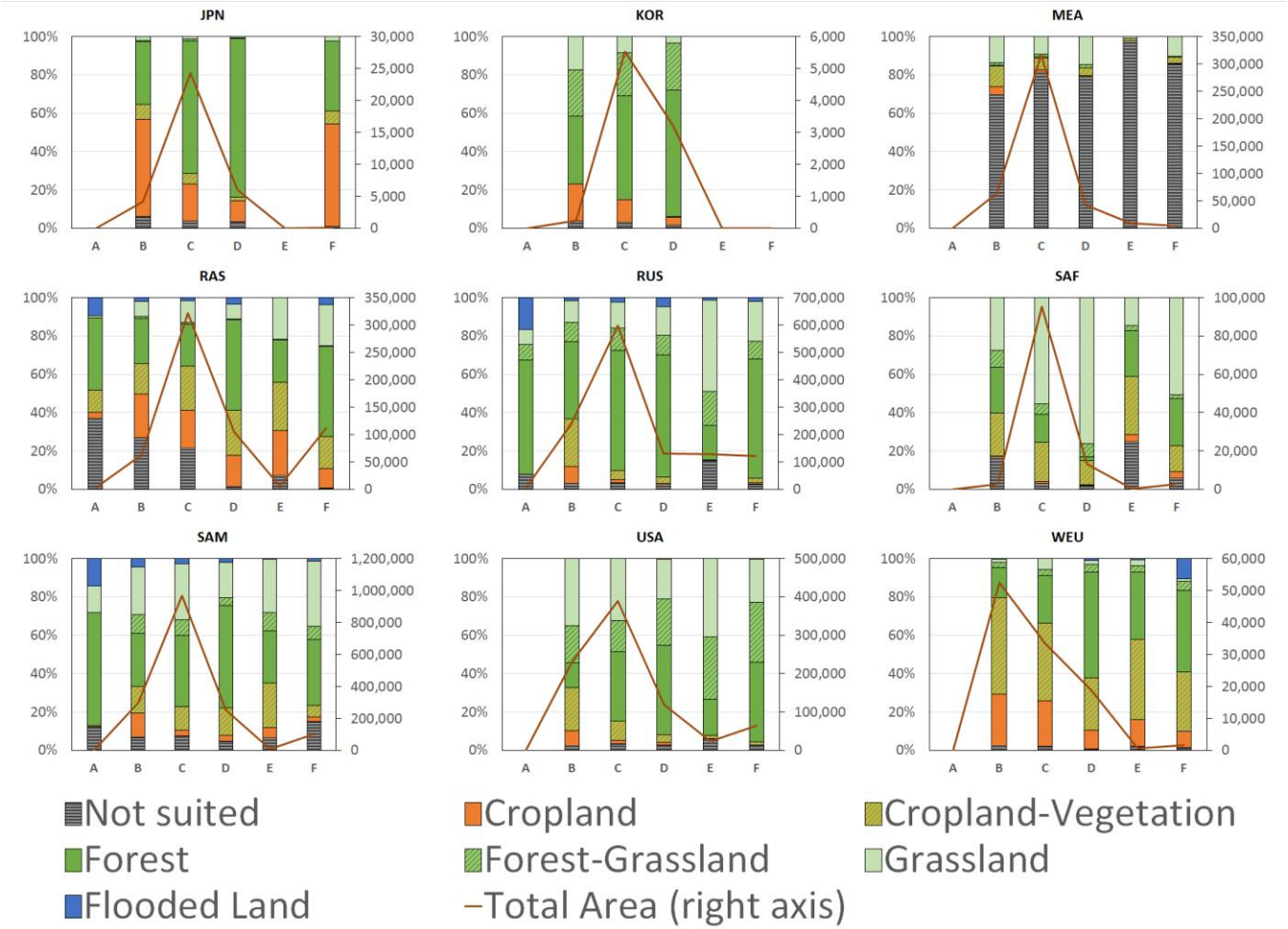


Figure 6-6 Aggregated land use and categories for all regions (part 2)

Legend: Land categories in % (left axis) and area in k hectares (right axis)

6.2.Land Use Change

As mentioned in the previous section, land use change is an important aspect of the dynamic behaviour of the land system. It basically involves the change from one land cover into another through human interference. An example of this is deforestation, where a certain area is changed from forest into another, usually grassland or cropland.

The example above is typical where, due to variation of the carbon stock, both underground and above the ground, there is a net emission of GHG to the atmosphere. However, there are changes which create a net removal of GHG from the atmosphere. These are known as "carbon sinks", since they present a net negative emission. Reforestation and afforestation are examples of such processes.

Since a spatially explicit carbon stock map was used, an average carbon stock was used for every region and land cover. The values, presented in Table 6-3, were taken from the "Good Practice Guide for LULUCF" (IPCC, 2003) and "Guidelines for National Greenhouse Gas Inventories" (IPCC, 2006). The values were calculated by using the estimated biomass stock above ground (t_{dm}/ha) multiplied by the carbon content (t_C/t_{dm}), resulting in the carbons stock (t_C/ha).

Thus, the estimated emissions due to land use change are calculated by following a mass balance equation, as follows:

$$Emission_{CO2} = \Delta_{Land\ changed} \cdot \left(CS_{before} - CS_{after}\right) \cdot \frac{44}{12}$$

Where CS_i stands for Carbon stock in.

Table 6-3 – Carbon stock of the Land Use categories

Region	Carbon Stock (tC/ha)				
	Forest	Forest-Grassland	Grassland	Crop-Vegetation	Cropland
AFR	130.0	69.0	8.1	6.5	5.0
AUS	64.0	34.2	4.4	4.7	5.0
BRA	108.5	58.3	8.1	6.5	5.0
CAM	108.5	58.3	8.1	6.5	5.0
CAN	23.0	13.6	4.3	4.6	5.0
CAS	30.0	16.5	3.1	4.0	5.0
CHN	61.0	32.0	3.1	4.0	5.0
EEU	61.0	33.9	6.8	5.9	5.0
IND	63.5	35.8	8.1	6.5	5.0
JPN	67.0	36.9	6.8	5.9	5.0
KOR	67.0	36.9	6.8	5.9	5.0
MEA	25.0	14.0	3.1	4.0	5.0
RAS	63.5	35.8	8.1	6.5	5.0
RUS	30.0	18.4	6.8	5.9	5.0
SAF	61.5	32.9	4.4	4.7	5.0
SAM	108.5	58.3	8.1	6.5	5.0
USA	70.0	38.4	6.8	5.9	5.0
WEU	61.0	33.9	6.8	5.9	5.0

Source: adapted from IPCC (2003), IPCC (2006) and UNEP (2015)

Once more, the methodology used in this study is a simplified approach, in order to include such aspects into the decision making process. So, whenever the demand for bioenergy increases the need for additional lands, the competition between the land use, either for agricultural production or to keep the carbon stock (e.g. for forests), is consistently taken into consideration within the model.

It is worth noting that the model developed in this study oversimplifies the behaviour and drivers for land change, such as deforestation, which may have strong influence from social and cultural background and, therefore, not determined solemnly by the economic drivers and fixed technical parameters determined in this study.

6.3.Agriculture

This section addresses the agriculture sector, which is basically the use of land areas to cultivate products, such as food, animals and bioenergy. In this section, four

aspects will be assessed in greater detail: food demand and diet scenarios; crops, considering production and yields; livestock, for producing meat, eggs, milk, etc.; bioenergy, which means dedicated crops for energy use.

6.3.1. Food and Diet

In order to assess the evolution of diet and food demand, the database available in FAO (2016) was used. The website provides a time series from 1960 to 2011, which includes 168 agricultural products, from crops and livestock, to processed crops and livestock. These products were categorized into 25 broader categories, with the exception of 30 uncategorized (such as several spices and condiments). The aggregated categories used are shown in Figure 6-7, separated by the type of product. The figure does not include exclusive bioenergy crops, which will be addressed in future sections.

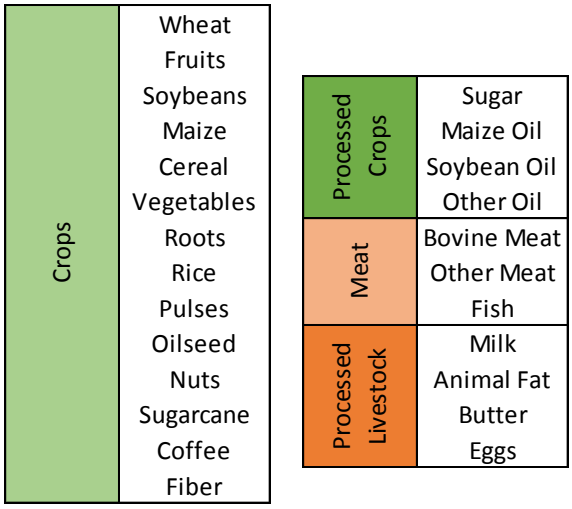


Figure 6-7 – 25 agricultural products

The same database addresses not only production, but consumption and food balance of countries, which enables the estimation of the diets for each of the 18 regions. Figure 6-8 presents the average diet, in kcal/hab/day, for every region and the world average, all for the base year.

Thus, a historic time series of demand of all 25 agricultural products and the average diet was estimated for each region. In order to evaluate the future demand of food, a simple profile was estimated for each product and region. Then, the data were

extrapolated until 2100 using a growth rate for every food category and country, resulting in the global evolution presented in Figure 6-9.

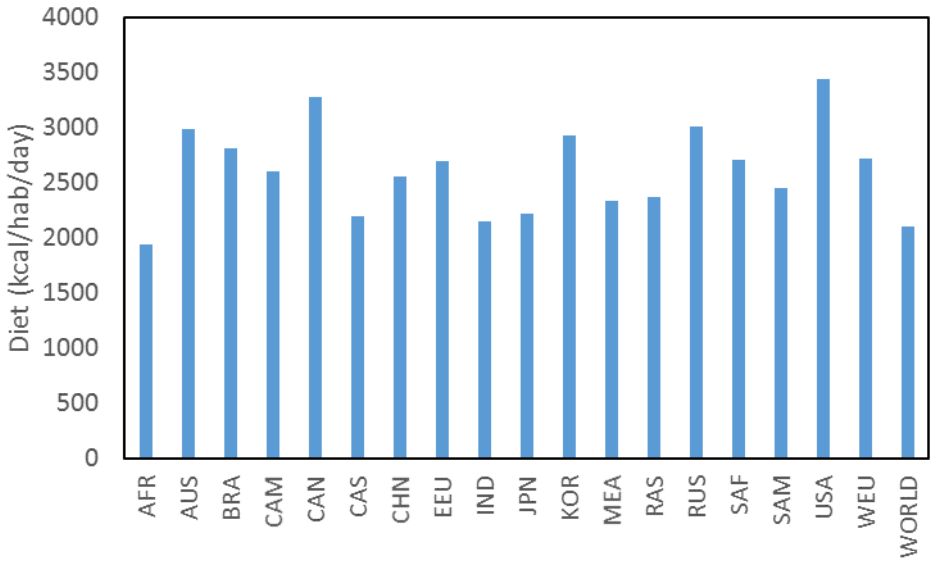


Figure 6-8 – Estimated diet across regions in 2010

Sources: FAO (2016)

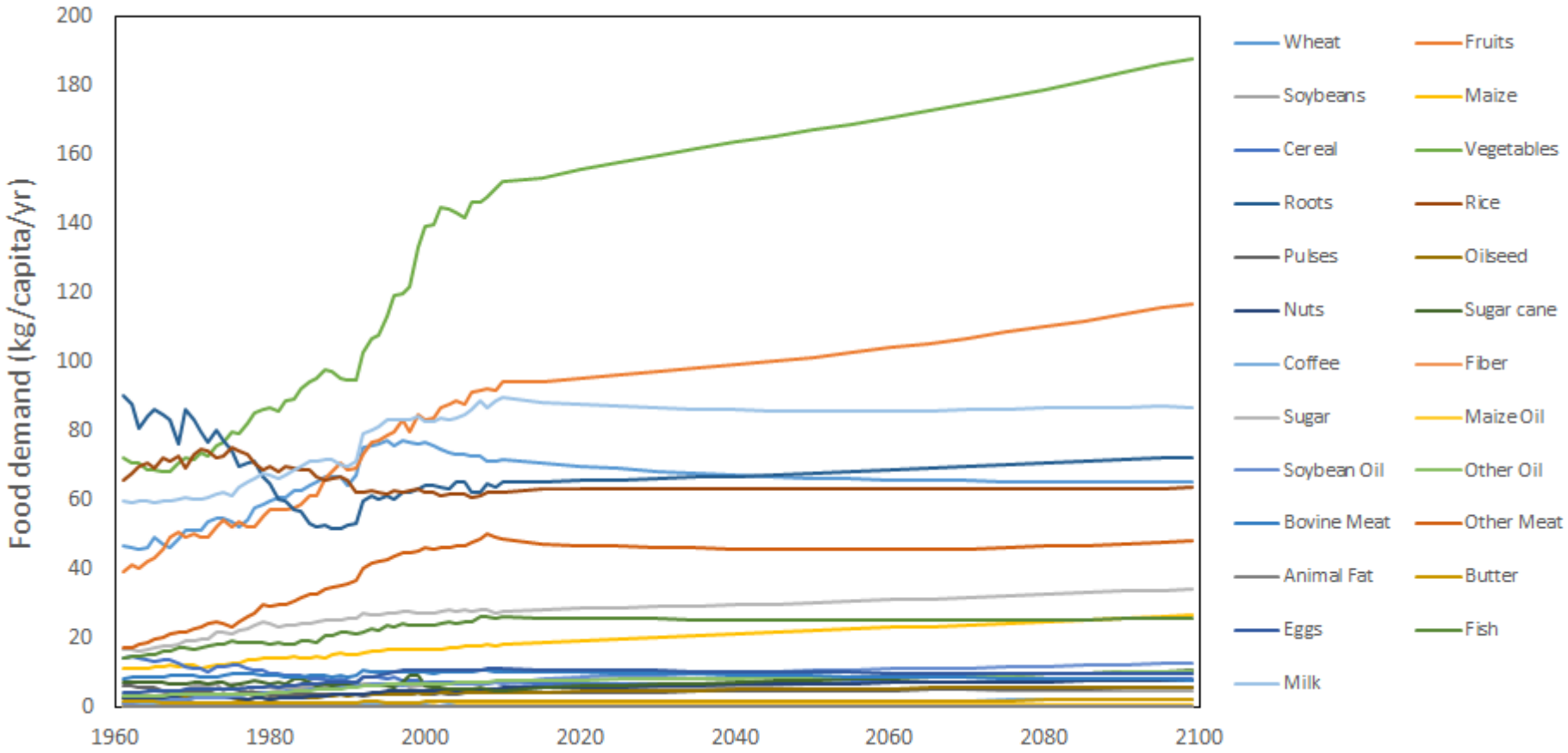


Figure 6-9 -Global food demand scenario

Source: Historic data from FAO, 2015

The estimated data for future consumption of food and agricultural products are presented in Figure 6-10 and Figure 6-11. The former presents the estimated historic diet from FAO (2016) data and the projection performed in this study. In the same figure, a range of future scenarios of dietary demand is presented. As it can be seen, this study not only falls into the range at all times, but is roughly close to the mean value of the range.

Figure 6-11 presents an indirect estimation of the estimated agricultural products. The methodology behind this figure is the same as in Figure 6-11. Not only that, but the estimates of this study once again fall closely to the mean value of the range for agricultural production.

An interesting difference between both figures is that the first has a narrower range of variation found in the literature than the second. In the base year, the diet ranges from 2700 to 3000 kcal/hab/day, whilst the estimated value from this study is around 2900 kcal/hab/day.

On the other hand, the range between the literature values for agricultural products ranges from 1200 to 2100 tonnes of dry matter per year. This study estimates a value of around 1650 t_{dm}/yr. An explanation for this difference lies on the conversion factors used, which involves converting food, in energy terms, to mass and then do dry matter.

Therefore, the demand for agricultural products was estimated, not including dedicated bioenergy crops. The values presented in this section were used as input data for the exogenous demand in the model.

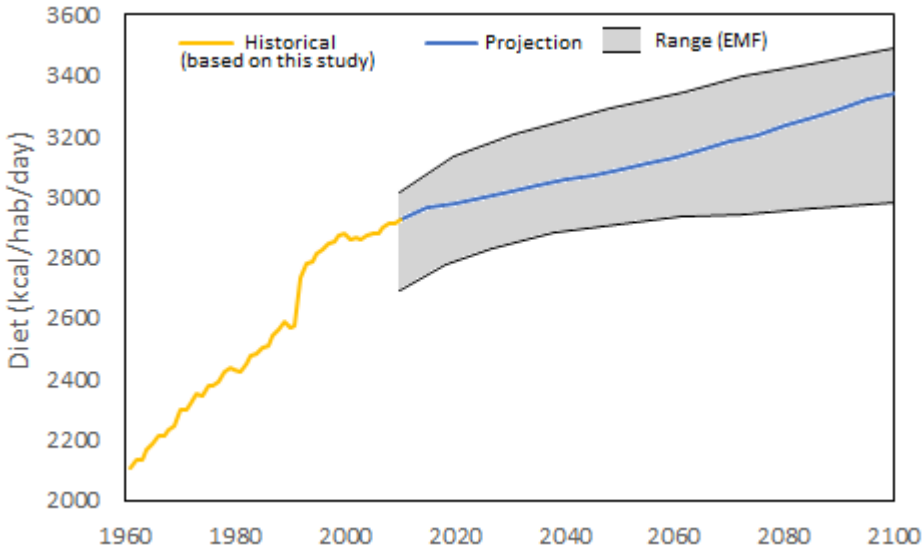


Figure 6-10 – Estimated diet consumption in (kcal/hab/day)

Sources: historical data estimated from FAO (2016) and scenario range from EMF (2016)

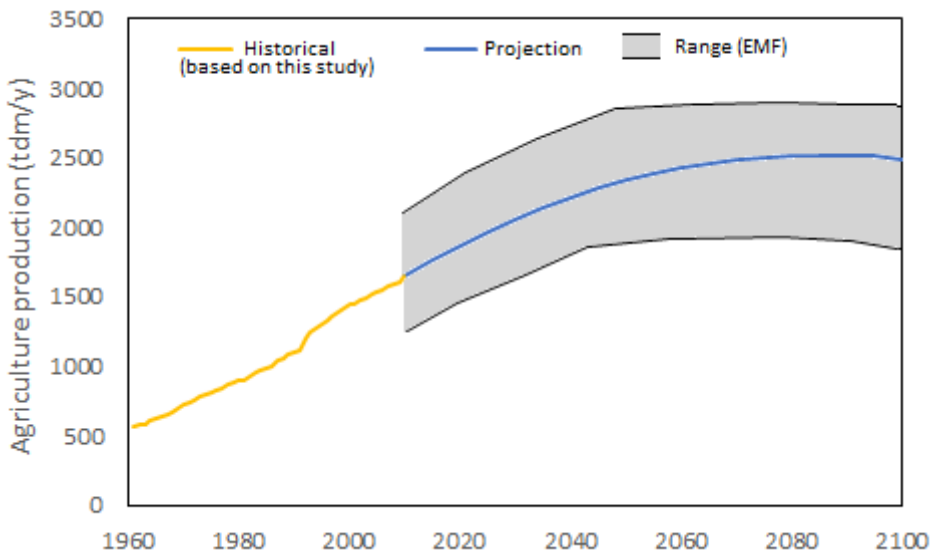


Figure 6-11 – Estimated agriculture production

Sources: historical data estimated from FAO (2016) and scenario range from EMF (2016)

Legend: tdm – tonnes of dry matter; EMF - Energy Modelling Forum

6.3.2. Crop production and yield

As mentioned in the previous section, FAO (2016) provides a comprehensive database for agricultural production and other technical data. In this section, only crops

will be assessed. As shown in Figure 6-7, crops are responsible for 14 out of the 25 agricultural products used in the model.

However, production is not the only aspect used to differentiate agricultural production between all regions. As it happens, yield is an important factor for assessing land use; it is the link between total production of a crop and the total area devoted to cultivating this crop.

Due to different technology, soil property and climatic conditions, the yield of a given crop can vary widely across the world. Figure 6-12 presents this behaviour for selected crops. Values not presented in the figure basically mean that there is no historic production of the particular crop in that region.

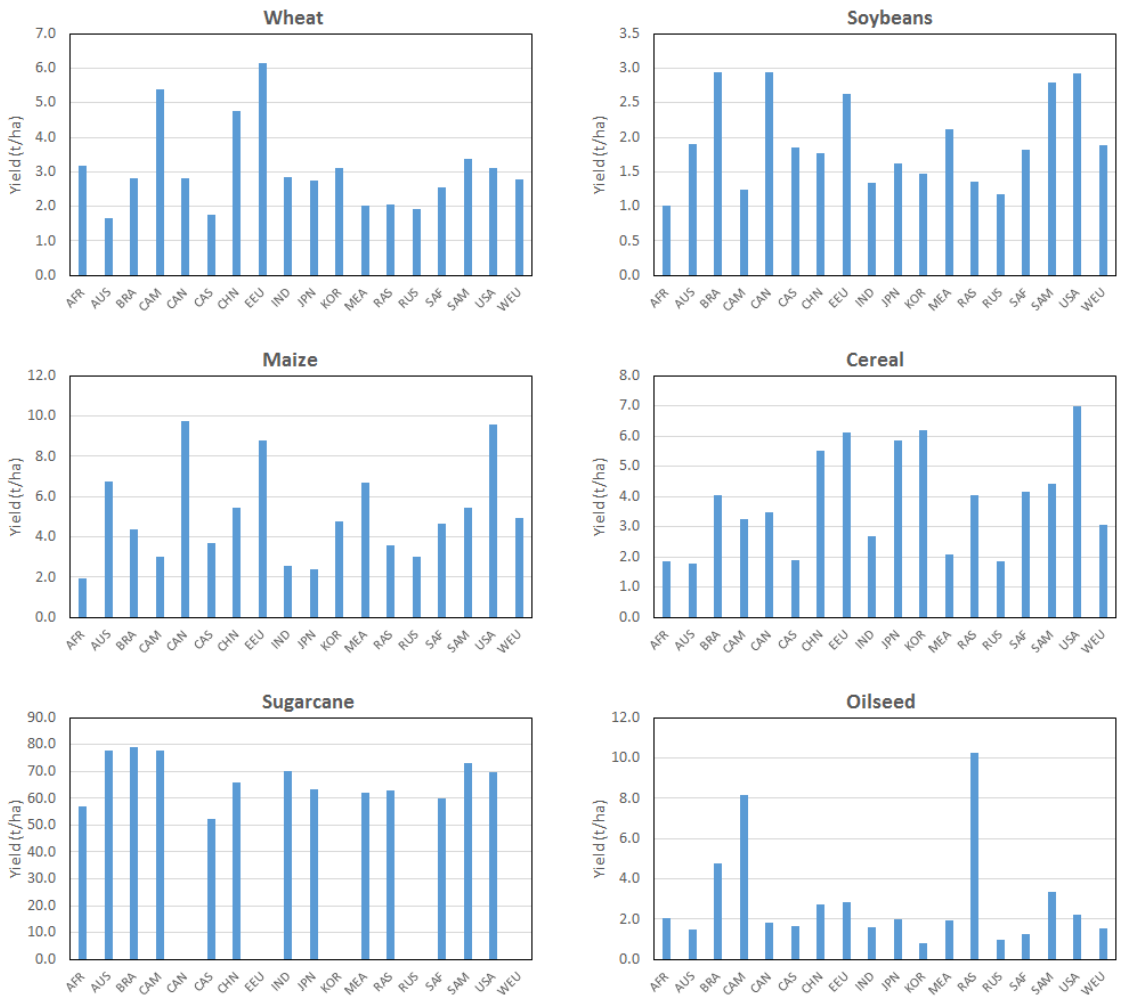


Figure 6-12 – Yields for selected crops across regions

Source: FAO, 2016

6.3.3. Livestock

Crops are not the only user of land within the agricultural sector. Animal husbandry is another important activity of the agricultural sector, which is responsible for the supply of food, more importantly meat, milk and eggs. This process of animal husbandry is commonly known as livestock.

In the FAO database, livestock includes several animals, such as: cattle, buffalo, horses, goat, sheep, chicken, turkey, rabbits, pigs and other birds. Due to the importance of cattle in the supply of meat and milk, cattle was separated from other livestock in this analysis.

Just as crops, cattle raising is also responsible for occupying large areas. However, just like crop yield, every region has its own "yield", which is presented in terms of animals per hectares. Figure 6-13 presents the estimated cattle occupancy, or yield, for every region.

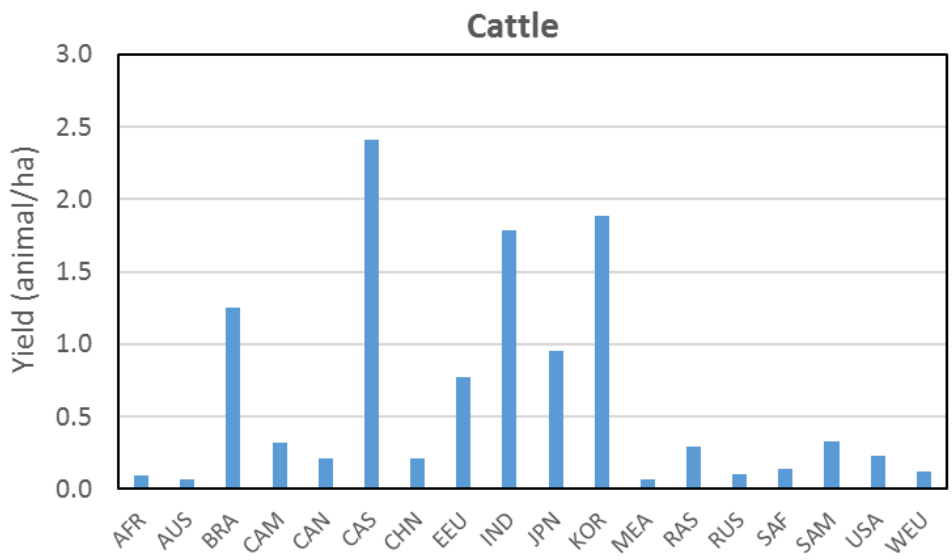


Figure 6-13 – Cattle livestock yield

Source: FAO, 2016

As it can be seen, the values range from near 0.1 to roughly 2.5 animals per hectare. This is an example of how different production techniques can affect the demand for land. All the data in this figure were estimated form FAO (2016).

Another important difference throughout the regions related to cattle husbandry techniques is the slaughter rate, which can be used as a proxy for estimating the average

age of the slaughtered cattle. For instance, a lower slaughter rate is related to a higher average age of cattle at the moment of the slaughter. In fact, decreasing the slaughter age (or increasing slaughter rate) is considered an improvement in productivity and it is also a mitigation option, since it decreases the average lifetime amount of methane emitted by the livestock. The estimated slaughter rates are presented in Figure 6-14.

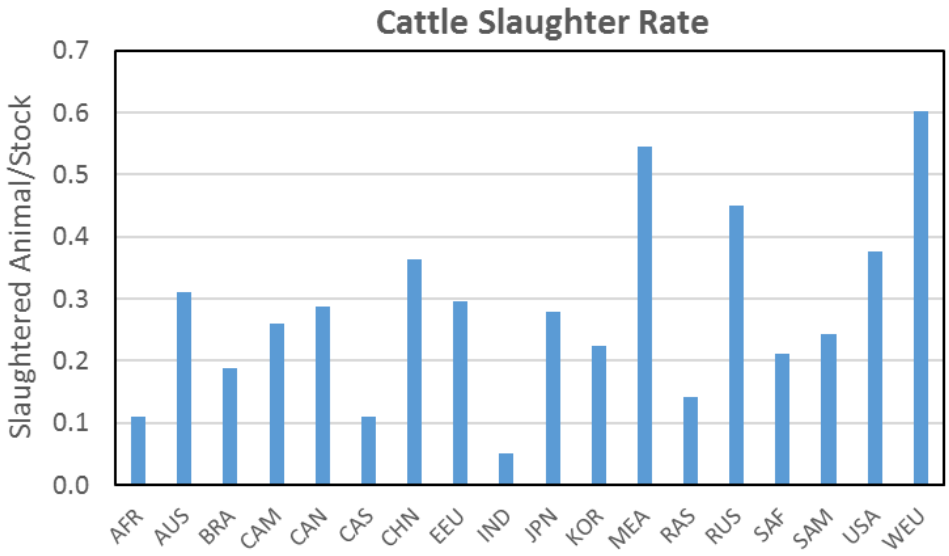


Figure 6-14 – Cattle slaughter rate for meat

Source: FAO, 2016

Cattle can be used for producing meat, therefore the need for slaughtering the animal. Nonetheless, it can also be used for producing milk, another important food product. Depending on the purpose of the cattle, their diets are different, which in turn relates to different emission factors due to enteric fermentation. Figure 6-15 presents the compiled data for emission factor of the average livestock of each region. It becomes clear that milk cattle consistently present a higher emission factor than meat cattle.

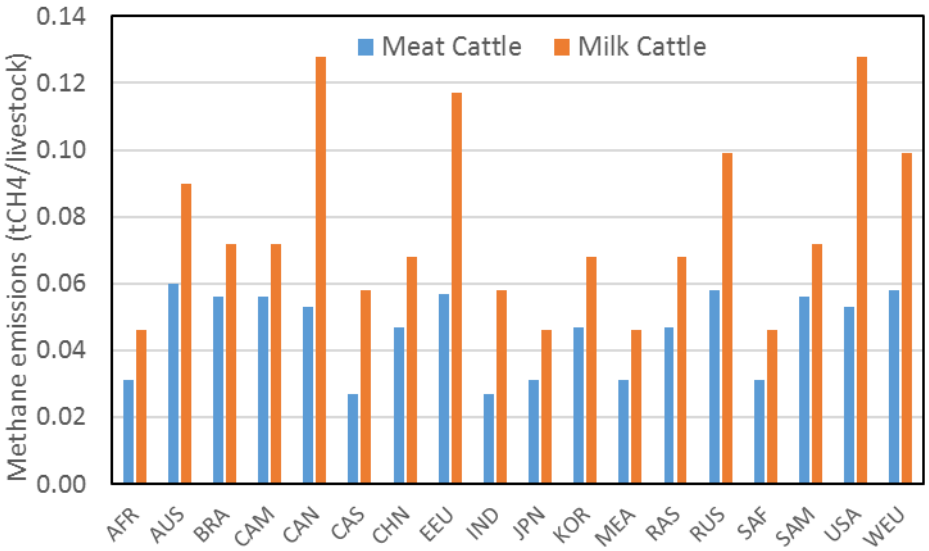


Figure 6-15 – Methane emissions for meat and milk cattle

Source: FAO, 2016

Nonetheless, cattle are not the only livestock considered in this study. Another important livestock in terms of food production are chickens, since they can be raised for producing meat and eggs. Since all the other livestock available in FAO (2016) are not significantly important in terms of both animal stock and meat production, they were categorized together with chickens.

Practically, combining all other livestock together with chickens almost had no impact on the average coefficients elaborated in this study. This is the case of the occupancy or, once again, the "yield" of other livestock. As it can be seen in Figure 6-16, the unit of measurement is thousand animals per hectare, due to the common practices of raising chicken.

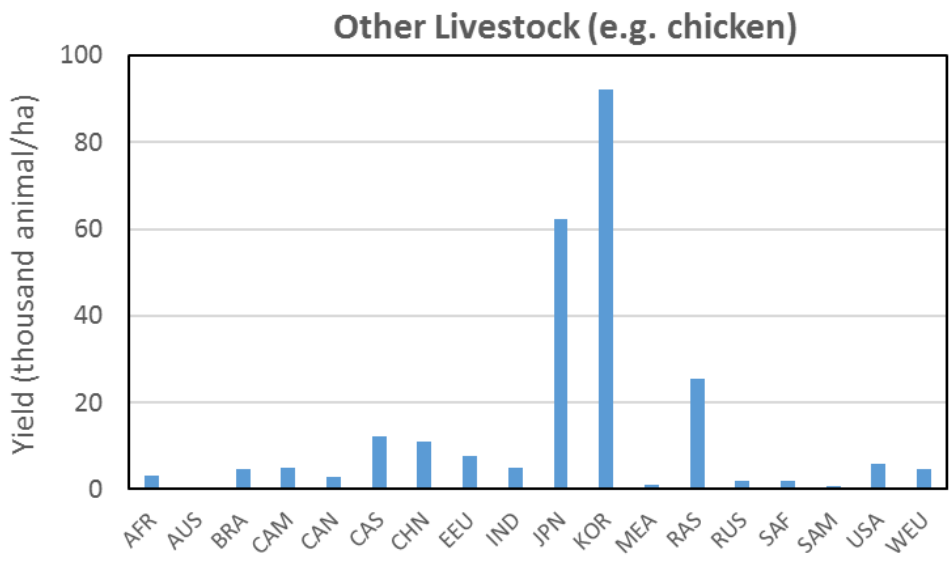


Figure 6-16 – Other livestock yield

Source: FAO, 2016

6.4.Bioenergy

Increasingly, agricultural crops and residues are seen as sources of feedstocks for energy to displace fossil fuels. A wide range of materials has been proposed for use, including grain, crop residue, cellulosic crops (e.g., switchgrass, sugarcane), and various tree species (IPCC, 2007b).

In the following sections, the feedstocks considered in this model for bioenergy production will be addressed, including primary sources and secondary sources, such as residues. In the last subsection, the energy conversion technologies will be discussed.

6.4.1. Primary biomass

As mentioned, several crops are already extensively used as feedstock for final energy production around the world, such as sugar feedstock and oilseeds, which are already intensively used for biofuel production.

All the abovementioned, feedstocks have been addressed in this chapter, even if the cultivation purpose was not bioenergy, such as sugar or oil crops. For example, sugarcane production is not only related to sugar production, but also first generation ethanol and cogeneration of heat and electricity by burning bagasse (and even straw). The

same could be said about soybean and other oil crops, which primarily are harvested to produce oil or protein, but can also be used to produce biodiesel (commercial name of fatty acid metil or etil Esther – FAME or FAEE).

Thus, most of the feedstocks for bioenergy have been addressed in the previous sections. However, there are two types of biomass that have not been addressed and whose harvests are dedicated to energy production: woody biomass and grassy biomass.

Woody biomass is a category of biomass, typically from trees and shrubs, including limbs, tops, needles, leaves, and other woody parts, grown in a forest, woodland, or rangeland environment, that are the by-products of restoration (USDA, 2003). Examples of woody biomass are eucalyptus, poplar and willow. They can be used for generating electricity, producing biofuels, and making biochemical such as adhesives, solvents, plastics, inks, and lubricants.

Grass biomass is, typically, perennial crops that are potential feedstock for bioenergy production, including heat, electricity, first and second generation biofuels. They can be used entirely in processing for fuel production. Examples of grassy biomass are mischanthus and switchgrass.

These two types of dedicated energy crops are options of crops available to the model, additionally to the 14 already described earlier. For both, average values for yield and heating values were considered. Woody biomass yield varied between 4 to 10 t/ha for poplar, from 4 to 12 t/ha for willow and 8 to 15 t/ha for eucalyptus. As for grassy biomass, the range of yield varied between 7 to 15 t/ha for mischanthus and 3 to 8 t/ha for switchgrass (FAO, 2008; IRENA, 2014; WEIH, 2009; HASTINGS *et al*., 2009). Figure 6-17 presents the regional yield of woody and grassy biomass.

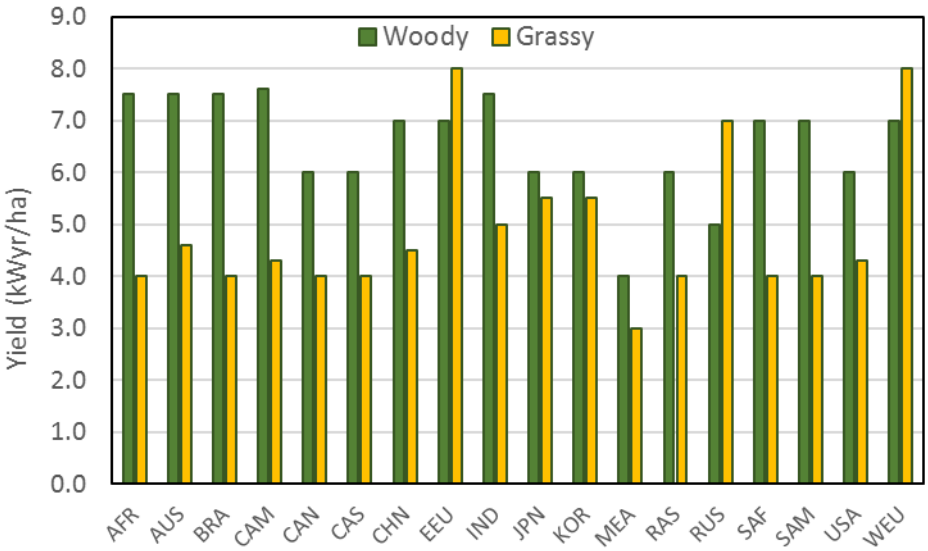


Figure 6-17 – Yield for grassy and woody biomass

Sources: Adapted from FAO (2008), IRENA (2014), WEIH (2009), HASTINGS *et al.* (2009)

6.4.2. Agriculture Residues

In the context of bioenergy, residues are typically defined as by-products associated with food production and the forest sector. Consequently, residue generation is driven by the demand and activity of the agriculture sector (DAIOGLOU, 2016).

Part of the residues potential is already used by the agriculture sector for several purposes, such as maintenance of ecological functions (DAIOGLOU, 2016) and fuel sources, especially for low income households in the rural area.

DAIOGLOU (2016) estimated the global supply of residues using the IMAGE-TIMER model. In this assessment, the author uses three levels of reside potentials: theoretical, which accounts for all aboveground straw and stalk; ecological, which excludes the required residue for avoiding environmental degradation; available, which excludes the use of residues as feed for livestock.

The study also provides a series of equations to estimate the Residue to Product Ratio (RPR), which is a function of the yield of a given crop (DAIOGLOU, 2016). Thus, using the estimated crop yield developed in this study, the coefficients available in DAIOGLOU (2016) and the total crop production, the residues potentials can be estimated. The estimated residues potentials (theoretical, ecological, available) for every region are presented in Table 6-4.

Table 6-4 – Estimated agricultural residues in 2010

Region	Residues (EJ)		
	Theoretical	Ecological	Available
AFR	4.7	2.6	1.4
AUS	0.9	0.5	0.3
BRA	6.3	3.5	1.8
CAM	1.7	0.9	0.5
CAN	1.3	0.7	0.4
CAS	1.8	1.0	0.5
CHN	7.2	4.0	2.1
EEU	8.1	4.4	2.3
IND	5.9	3.2	1.7
JPN	0.1	0.1	0.0
KOR	0.0	0.0	0.0
MEA	0.8	0.4	0.2
RAS	7.9	4.4	2.3
RUS	1.4	0.8	0.4
SAF	0.3	0.2	0.1
SAM	3.4	1.9	1.0
USA	9.0	4.9	2.6
WEU	1.6	0.9	0.5
World	62.4	34.3	18.1

In the global model, the ecological and available potentials are estimated according to the supply of all 14 crops, described in previous sections. Thus, the future residues potential is estimated and made available to the energy sector. The conversion technologies available for crop residues include generation of heat, electricity and biofuels, which will be presented in the next subsection.

It is important to note that bagasse is not included in Table 6-4 due to the characterization used in DAIOGLOU (2016). Bagasse is an important by-product from sugarcane crops and it is almost completely used for energy production. The average yield for bagasse used in the model is 0.3 tonne of wet bagasse per tonne of sugarcane (SEABRA AND MACEDO, 2011).

Additionally, the residues that are not used for energy production are considered to be burnt directly in the crop fields. Therefore, there are two major sources of GHG emissions related to crop residues: emissions from decomposition of nitrogen in crop residues left on managed soils (IPCC, 2006), and low-efficiency combustion of crop residues in the fields, which causes methane emission.

6.4.3. Bioenergy conversion technologies

This section presents some of the conversion options available for biomass in the model. The conversion of biomass into electricity was presented in the previous chapter. Thermochemical conversion of biomass to hydrogen and synthetic liquids are also available, as noted in the previous chapter. In this chapter, the focus lies on the conversion of biomass and residues into traditional biofuels, such as ethanol and biodiesel. This includes both first and second generation ethanol. Table 6-5 presents the conversion efficiencies and production cost for all traditional biofuels, separated by feedstock.

Table 6-5 – Conversion yields and production costs of biofuels

Feedstock		Sugarcane	Corn	Wheat	Woody	Grassy	Beet	Bagasse	Residue*
Product		Ethanol	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Yield	l/t_{feed}	85	375	390	340	265	100	155	155
Investment	$/kW	500	575	675	1700	1700	750	2800	2800
Fixed O&M	$/kW/yr	25	21	22	43	43	19	70	70

Feedstock		Woody	Soy Oil	Maize Oil	Animal Fat	Oilcrops**
Product		Methanol	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Yield	l/t_{feed}	430	215	215	1000	230
Investmen	$/kW	1000	650	650	650	650
Fixed O&M	$/kW/yr	25	16	16	16	16

* Considering lignocellosic residue, such as straw.
** The same efficiency and costs were used for several other oilcrops.

Source: Adapted from USDA (2006), HAMELINCK AND HOOGWIJK (2007), IEAGHG (2011), GERSSEN-GONDELACH et al (2014), MANOCHIO (2014), DAIOGLOU (2016), DAIOGLOU et al (2016),

For all technologies presented in the upper part of Table 6-5, adding carbon capture to the bioenergy production process was considered. The fermentation step of both conventional and advanced bioethanol production is similar and per litre of ethanol the same amount of biogenic CO_2 is co-produced (IEAGHG, 2011). The emission of CO_2 in the fermentation process is estimated at roughly 0.95 tCO_2 per tonne of ethanol produced.

The CO_2 concentration in the off-gases of an ethanol production plant (conventional or advanced) is about 99 % on a dry volumetric basis. This is after the removal of water from the product gas stream. The CO_2 leaves the fermentation process at atmospheric pressure and moderate temperatures of about 25-50 degrees Celsius. Further treatment is not deemed necessary and the CO_2 can be compressed in the

multistage compressor to the required transport pressure of 100-150 bar, typically (IEAGHG, 2011).

7. Model Simulations

7.1. Model statistics and scenario protocol

This chapter presents the scenario protocol and the results of this study. The timeline of the model here developed is from 2010 to 2100, with a 5 year time step until 2050, and 10 year step afterwards until 2100. There are 26 energy levels and 507 energy forms per region. However, since a single energy form can be allocated into several different energy levels, the total number is not an indication of all the different energy vectors available within the model. For instance, electricity can be allocated into secondary energy, final energy and for every end-use sector.

As previously explained, the model here developed has several constraints to take into account when looking for a solution. These can be differentiated between two main types: exogenous demand and additional constraints. For the former type, the model has 26 energy-related demand vectors and 22 agricultural demand vectors for every region.

Additionally, there are 1623 constraints, of which 7 allow accounting GHG emissions by source. It is worth noting that there are only three GHGs accounted for in this study: carbon dioxide, methane and nitrous oxide. The Global Warming Potential, or GWP, was used as a metric to relativize the emissions of these three gases. The methodology was based on the IPCC Fifth Assessment Report (IPCC, 2014) for a 100 years' time horizon. This will be referred to as "AR5 GWP-100".

Also, there are 1470 constraints that function for accounting land use and land use change throughout the time steps. The remaining constraints are energy-related, which allow accounting for carbon injection in storages and spent nuclear fuel storage.

Technology-wise, the model has 7114 technologies per region. Finally, there are 168 resource categories for oil, gas, coal and uranium.

As mentioned in the second chapter, one of the objectives of this study is to assess the RCP scenarios with the model here developed. Additionally, in chapter 3, the macroeconomic scenario selected for this assessment was the SSP2.

Hence, according to the compatibility matrix[11] between the SSPs and the RCPs, there are five scenarios compatible with the SSP2. These scenarios are presented in Table 7-1, with the tag used to relate to the appropriate scenario. Thus, all four RCP scenarios will be assessed as well as a reference scenario. The following sections present the quantitative results of this study.

Table 7-1 – Scenario protocol and result tag

Scenario	Result Tag
Reference	Res-REF
RCP 8.5	Res-RCP85
RCP 6.0	Res-RCP60
RCP 4.5	Res-RCP45
RCP 2.6	Res-RCP26

The GHG emission constraint was applied to the global emissions of the model. In each RCP scenario, the total GHG emissions was determined as lower than or equal to the RCP emission profile, presented in chapter 2. Therefore, each of the 18 regions were free to acomodate themselves, with their mitigation potential and opportunities, to keep within the global emission cap.

7.2.Reference Scenario (Res-REF)

The first scenario is the Reference scenario. Basically, it is a scenario without any mitigation efforts and, thus, with no additional policies for constraining GHG emissions. In this sense, the model is completely free to decide on the production of energy sources, energy consumption profile of every sector and region, land use change and agriculture production.

Hence, this is expected to be a scenario with relative high GHG emissions, due to the economic advantage of conventional fossil fuels use, such as coal and oil. Moreover, land emissions are also expected to be relatively high since there is no economic driver to improve production methods or use land with higher costs due to lower yield or

[11] See chapter two, section three.

distance. Also, there are no barriers to prevent deforestation or other land use change processes which might lead to an increase of GHG emissions.

7.2.1. GHG Emissions

The estimated global GHG emissions are presented in Figure 7-1, with the detailed emissions by source and pollutant in Figure 7-2. The total GHG emission in 2010 is estimated at 49.6 $GtCO_{2eq}$, whilst the literature ranges from 48.8 to 50.7 (KAINUMA *et al*., 2011; IIASA, 2013b; VAN VUUREN, 2013; PEREZ *et al*., 2014). In the base year, energy-related emissions and land-related emissions[12] were estimated at 33.2 $GtCO_{2eq}$ and 16.4 $GtCO_{2eq}$.

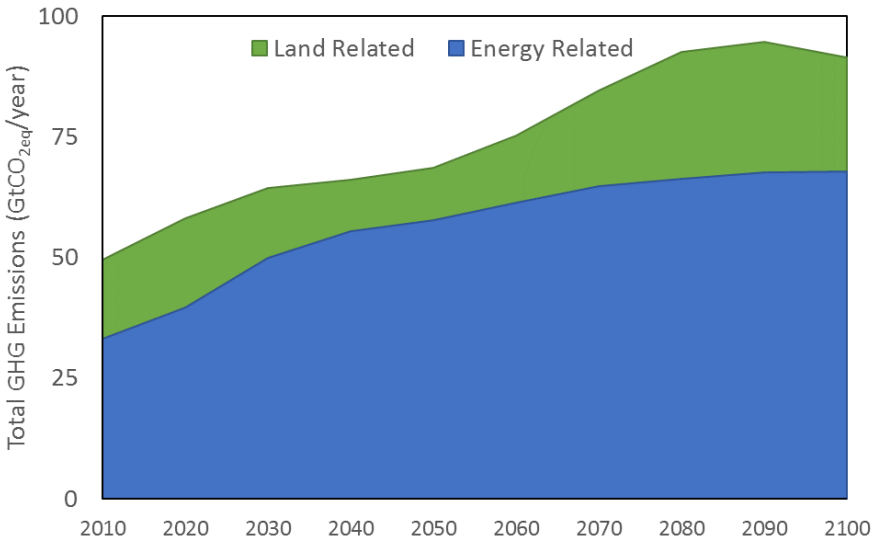


Figure 7-1 – Res-REF GHG emission

Figure 7-2 suggests that all energy-related gases and non-CO_2 gases of the land system continue to grow until the end of the century. However, the apparent odd behaviour of the CO_2 emissions due to the land system is consistent with the land use change estimated by the model, which will be detailed in the next section, which will address the land system specifically.

[12] In this study, energy-related emissions include industrial processes and municipal waste emissions. Even though these emissions are not related to fuel combustion, these two sectors are linked to the energy system and, therefore, aggregated to it.

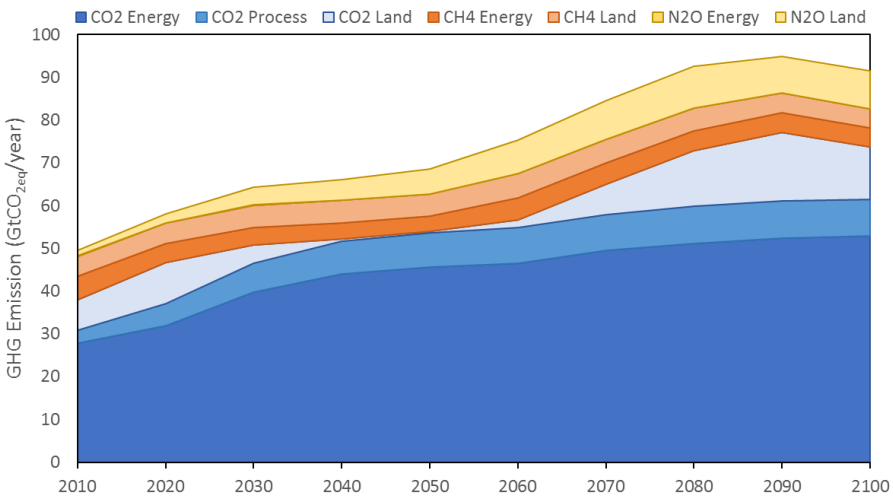


Figure 7-2 – Res-REF GHG emissions by pollutant and source

The energy-related emissions grow consistently, but not constantly, during the timeline, with an average growth rate of 0.8% per year. The actual evolution of the energy-related GHG emissions is presented in Figure 7-3 relative to available scenarios in the literature. The scenarios depicted in this figure are SSP2 Reference scenarios from three different IAMs, namely MESSAGE (named IIASA to avoid any confusion), AIM and POLES.

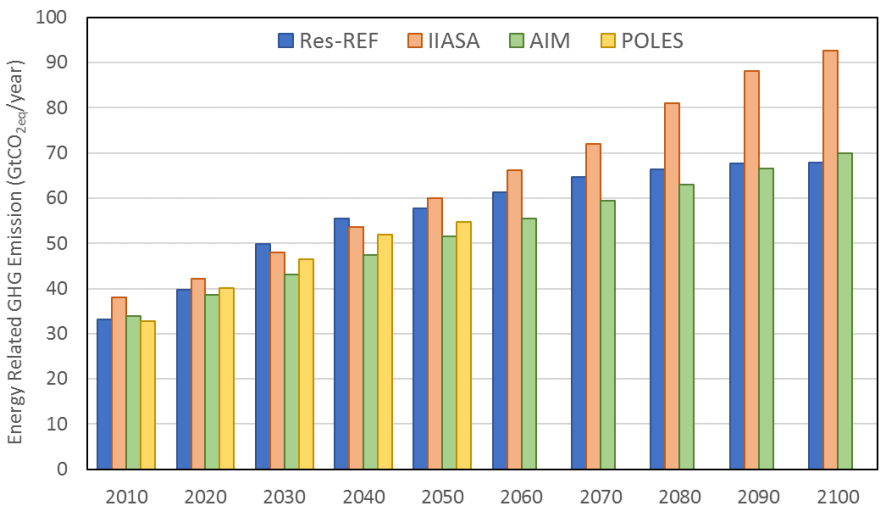


Figure 7-3 – Literature comparison for reference SSP2 energy-related GHG emissions
Source: IIASA (2013b), KOINUMA *et al*. (2011) and KITOUS AND KERAMIDAS (2016)

Despite the fast growth in emissions until 2040, the overall behaviour of the GHG emissions profile of this study is within the range of the literature. In fact, after the 2050 the profile is convergent with the AIM results (KOINUMA *et al*., 2011). Actually, all

results are close up to 2050. The main difference occurs after 2050 between IIASA and the other two SSP2 scenarios, Res-REF and AIM.

The relatively consistent results with the literature are also addressed in Figure 7-4, compared to a wide range of results that is presented in VAN VUUREN (2013). The results of the Res-REF scenario are consistently in the lower half of the range at all times, suggesting a SSP2 scenario with relative lower emissions, but definitely within the range found in the literature.

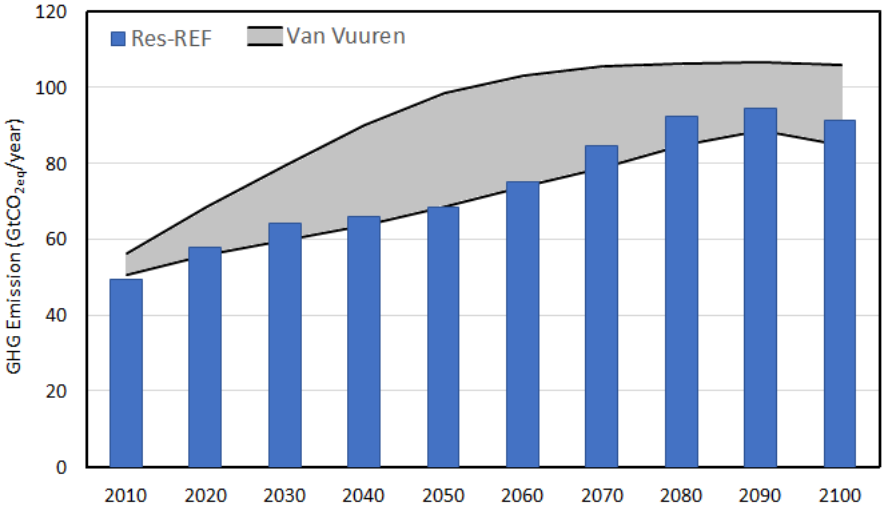


Figure 7-4 - Literature range for reference SSP2 GHG emissions
Source: range from VAN VUUREN (2013) and results in blue

The results of the GHG emissions profile are compared to the RCP scenarios in Figure 7-5. Interestingly, the Res-REF scenario is not only well below the scenario with the highest warming, RCP 8.5, but is relatively close to the RCP 6.0. This suggests that the Res-REF scenario is likely to induce a global surface temperature change increase (relative to 1986–2005) between 2.2°C (RCP 6.0) and 3.7°C (RCP 8.5), but relatively closer to 2.2 °C[13].

[13] Based on the mean values of global surface temperature change relative to 1986–2005, available in IPCC (2014). The full range of RCP 8.5 is between 2.6°C and 4.8°C and for the RCP 6.0, between 1.4°C and 3.1°C. Ergo, the warming induced in the Res-REF scenario could easily be different than the suggested value. Additionally, the range for the RCP 4.5 is between 1.1°C and 2.6°C with a mean increase of 1.8°C. The last RCP, RCP 2.6, is very unlikely to exceed 2°C, with a mean value of 1.0C, ranging from 0.3°C to 1.7°C.

Hence, the results suggest that there is an incompatibility between the SSP2 and RCP 8.5 scenarios, as some of the literature suggest (KAINUMA *et al*., 2011; KRIEGLER, *et al*., 2012; PEREZ *et al*., 2014).

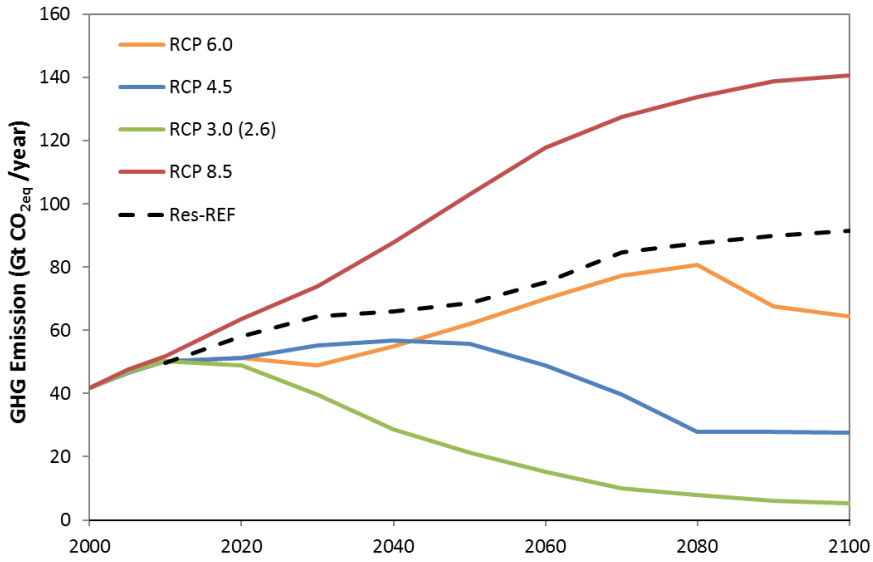


Figure 7-5 – Comparing Res-REF GHG emissions with different RCPs

Source: own compilation using data from IIASA (2013a)

Another interesting information that can be inferred from this figure is that the additional effort to achieve the emissions profile of RCP 6.0 and RCP 4.5 is relatively low until 2080 and 2050, respectively. Thus, it seems that under the SSP2 scenario developed in this study, the efforts needed to achieve a mean surface temperature increase of below (or about) 2°C relative to 1986–2005 is relatively small.

7.2.2. Land Use and Land Use Change

This section will explore the results for the land system in the Res-REF. In this scenario, the global land cover barely changes until 2100, as can be seen in Figure 7-6. However, a closer look indicates land cover changes, as presented in Figure 7-7.

This figure presents the cumulative land cover changes. Negative values are attributed to land cover which lost area and positive values are attributed to the land that gained area. Thus, the sum of the total positive and negative changes, for every year, is close to zero.

Results show that the cumulative total land cover change in 2100, relative to 2010, is of approximately 0.4 Gha, accounting for roughly 3% of the global land area. Overall, Forests are the greatest loser of cover, whilst Croplands are the greatest winner of changed land. Interestingly, Grasslands present a positive land change in 2020, but are consistently converted towards other land covers (most likely croplands) until 2100, when the total grassland cover is lower than the original in 2010.

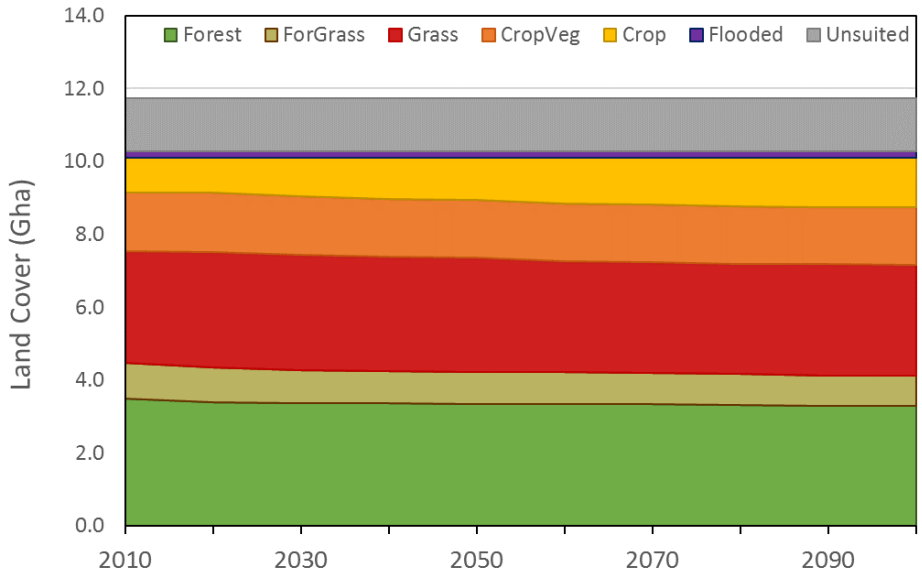


Figure 7-6 – Land cover for Res-REF

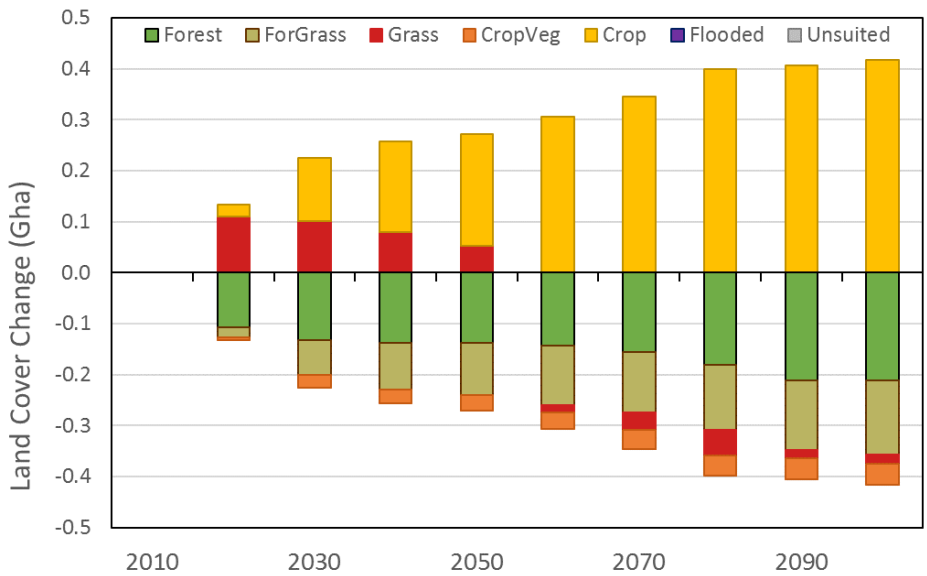


Figure 7-7 – Detailed cumulative land cover change for Res-REF

7.2.3. Primary Energy

This section explores the results for the energy system in the Res-REF scenario. The most common indicator used in the literature to compare long-term scenarios in IAMs is the total primary energy production or demand. In a regional or a national context, these two are widely different since a region can export and import energy products, thus differentiating production (as a part of supply) from consumption (demand). However, in the global context, primary energy supply and demand are expected to be the same, disregarding any unused energy products, losses or storage and stocking.

The total global primary energy demand is presented in Figure 7-8[14]. The estimated value in 2010 is of about 600 EJ. The Res-REF scenario presents a "S-shaped" consumption of primary energy, more than doubling the primary energy consumption until 2100. In term of energy source, the largest increase is, by far, related to coal consumption.

After 2020, oil remains the second most important energy source until 2100, increasing merely 0.7% a year. The highest relative increase since 2010 is for solar, with an average increase of about 26% a year until 2100. Despite this, this increase is almost invisible in Figure 7-8, due to its relatively low starting share in primary energy consumption, estimated in 2100 as around 7 EJ. Other important energy sources are biomass and nuclear, with growth rates of 1.9% and 1.1% per year, respectively, till 2100.

[14] All primary energy calculations in this study were made by using the physical energy content method, as explained in further details in IEA (2016).

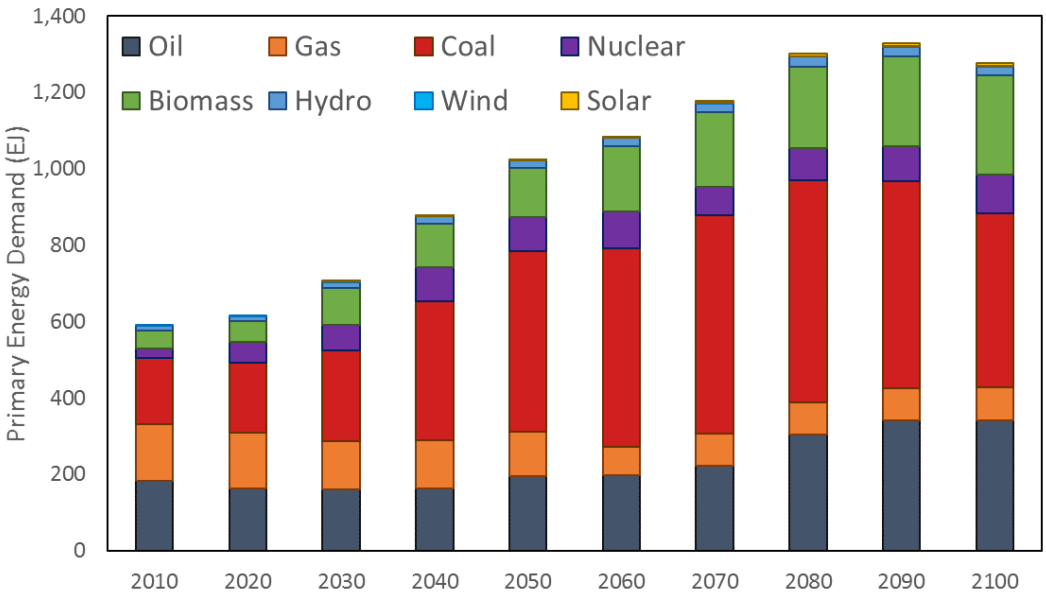


Figure 7-8 – Global primary energy demand (EJ) in Res-REF

The profile for primary energy consumption is compared to literature values in Figure 7-9. The results for AIM in KOINUMA *et al*. (2011) are presented in comparison to this study. Up until 2080, the results show a convergence with AIM. Also, this figure shows an estimated range for primary energy consumption in 2100 from VAN VUUREN (2013). The results of Res-REF for 2100 are close to the mean value of the range, which suggests a valid result.

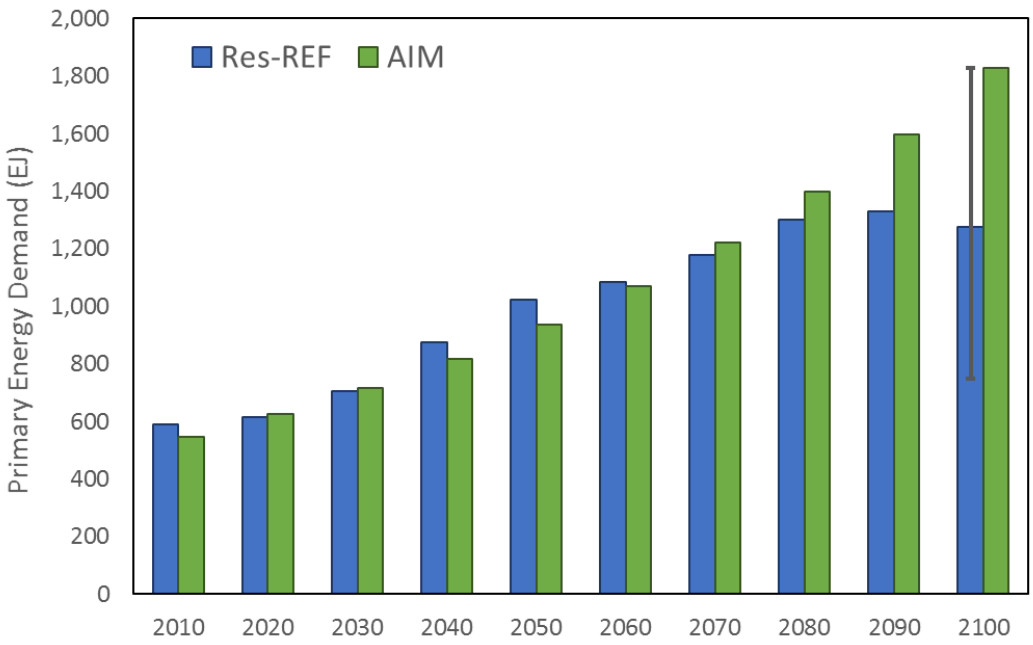


Figure 7-9 – Literature comparison of global primary energy demand (EJ)
Source: AIM data from KOINUMA *et al*. (2011) and 2100 range from VAN VUUREN (2013)

7.2.4. Brazil

This section focuses on the Brazilian results in Res-REF. Primarily, GHG emissions for Brazil are presented in Figure 7-10, by source, and Figure 7-11, by source and pollutant. At base year, the energy-related emissions were estimated at about 568 $MtCO_{2eq}$ with AR5 GWP-100. Values from the literature, using the same methodology, were estimated at roughly 585 $MtCO_{2eq}$ (KOBERLE *et al*., 2015; Schaeffer *et al*., 2015).

The second figure suggests that land-use-change emissions continue to play a role until 2030, mostly related to deforestation. Also, an isolated peak of land-related CO_2 emissions is observed in 2060, shifting the GHG emissions profile away from a smooth behaviour. The reason for this peak is presented in Figure 7-14 and will be discussed after presenting the land cover changes.

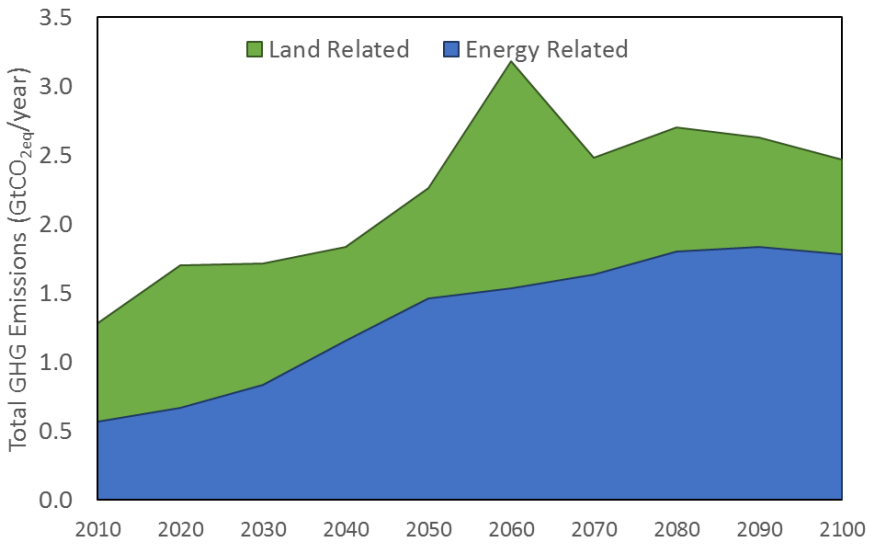


Figure 7-10 – Res-REF-BRA GHG-emission

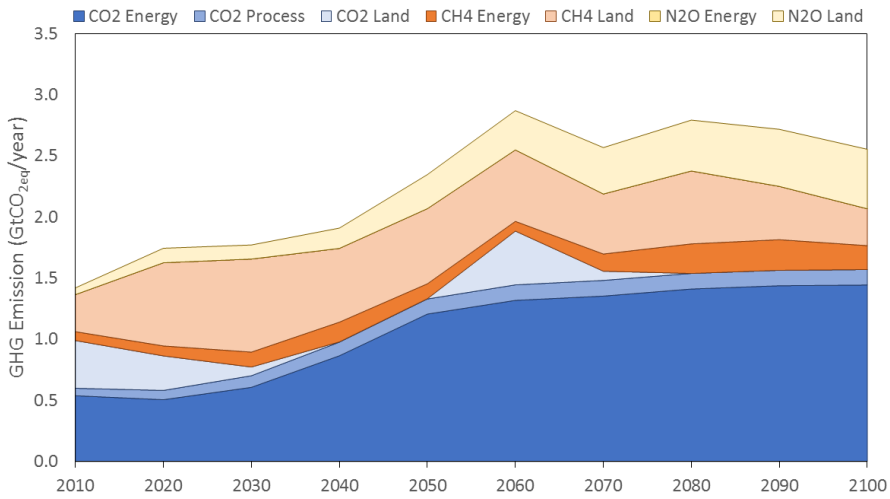


Figure 7-11 – Res-REF-BRA GHG-emission by pollutant and source

Since no literature was found detailing the Brazilian results under SSP2, the results of this study were compared to other studies found in the literature. KOBERLE *et al*. (2015) and SCHAEFFER *et al*. (2015) assess national GHG emissions under several scenarios using MESSAGE-Brazil (MSB8000). These studies use different macroeconomic scenarios, which have roughly the same population scenario, but slightly different GDP scenarios. Both have results only until 2050. The findings for energy-related emissions are presented in Figure 7-12.

Results show lower emissions then the reference scenarios in the literature until 2040. Also, GHG emissions up until 2040 are relatively close to KOBERLE *et al*. (2015), which considers a more moderate GDP growth than SSP2. However, after 2040, the Res-

REF emissions increases, being slightly higher than the study with the largest GDP growth, SCHAEFFER *et al*. (2015).

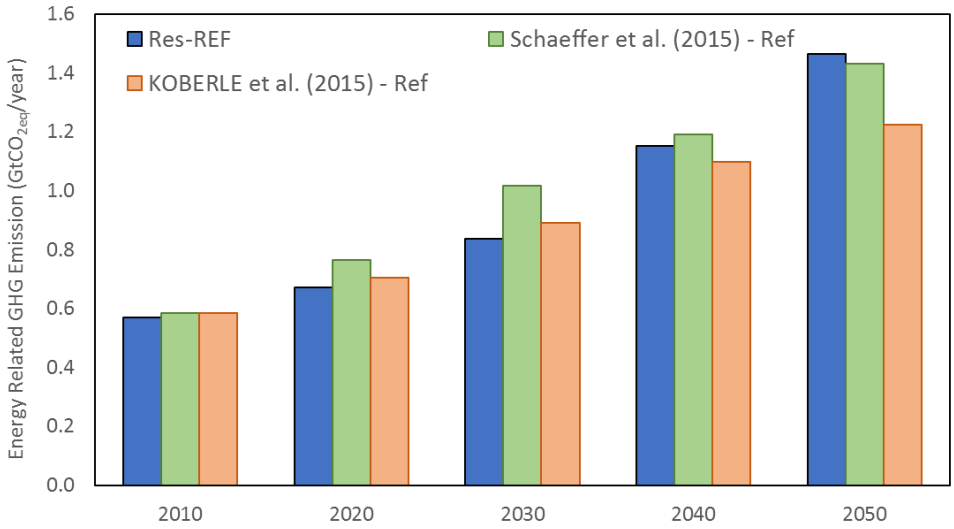


Figure 7-12 – Literature comparison for energy-related GHG emission in Brazil
Sources: KORBELE *et al*. (2015) and SCHAEFFER *et al*. (2015)

As for the land system, there are two important land cover changes in Brazil in the Res-REF scenario: deforestation until 2025 and conversion of grassland into cropland in 2060. The latter change is responsible for the peak in GHG emissions mentioned earlier.

The results for land cover and land cover change can be seen in Figure 7-13 and Figure 7-14. The latter shows that forests are converted into grasslands, which are partially converted into cropland until the end of the century. This explains the peak in emissions from the land system, as presented in Figure 7-11.

It is also worth noting that the peak in emissions result from a “step function” behaviour from the land use change. This behaviour is mostly explained by the linear characteristics and time resolution of the model, which favours a larger land change in a single year, instead of spreading the overall changes into the following years.

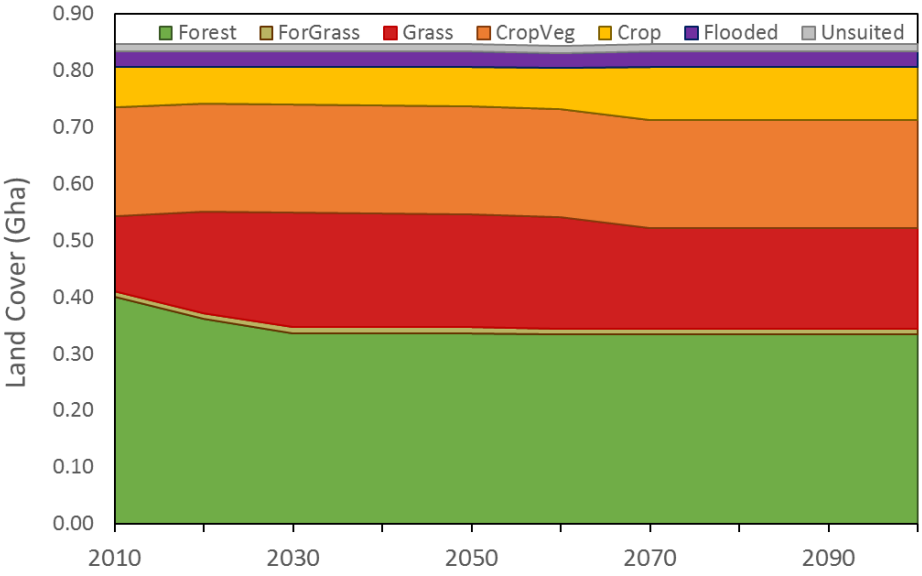


Figure 7-13 – Brazil land cover for Res-REF

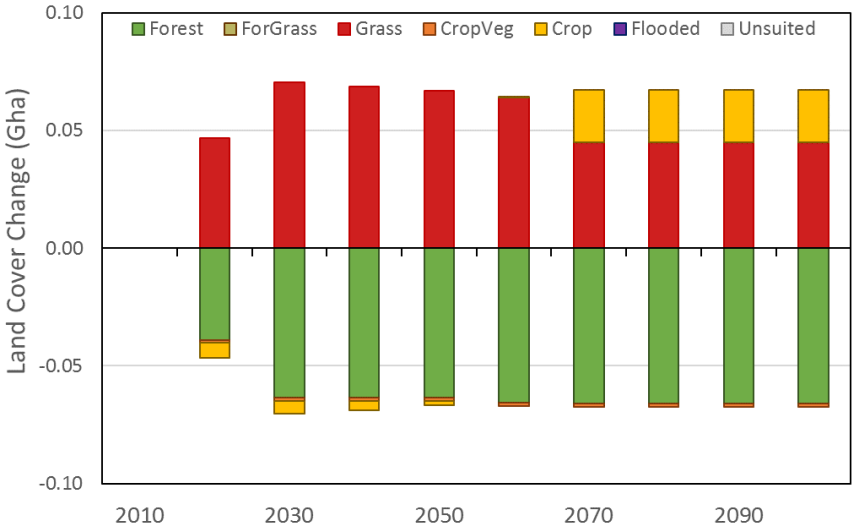


Figure 7-14 – Detailed cumulative Brazilian land cover change for Res-REF

As for the energy system, the results for the primary energy demand in Brazil are presented in Figure 7-15. In addition, imports and exports of energy products are accounted in order to estimate the total national demand. As can be seen in the figure, coal is widely expanded in the Brazilian energy system, not only for electricity production but also in the consumption of the final consumers, most importantly Industry. Oil demand fluctuates until 2100, with demand decreasing from 2010 until 2050, and increasing again until the end of the century.

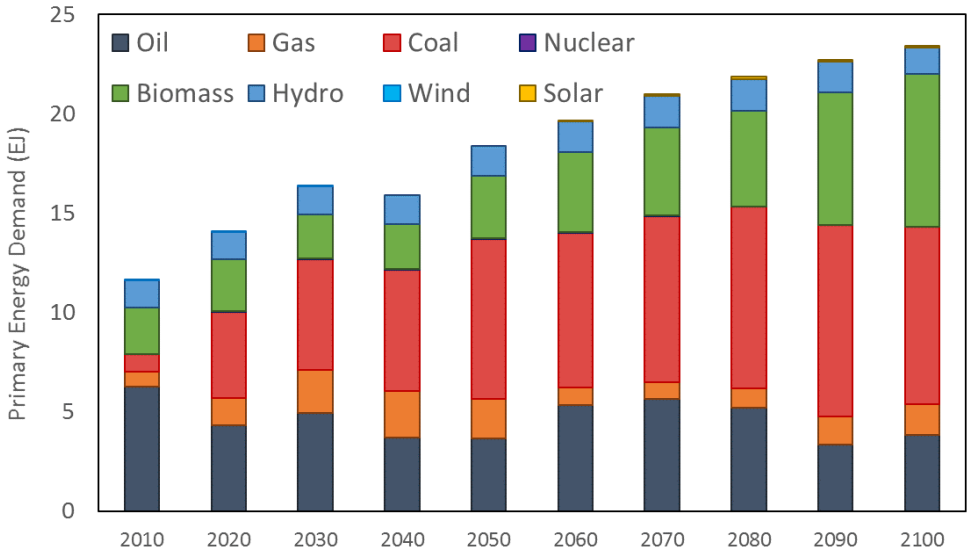


Figure 7-15 – Brazilian primary energy demand (EJ)

The estimated primary energy consumption in Res-REF for Brazil is compared to SCHAEFFER *et al*. (2015) in Figure 7-16. The most notable difference is for oil, which is lower than the figures found in the literature, and coal, which is relatively higher. Natural gas, biomass and wind are relatively consistent between both scenarios. The high increase in coal use partially explains the higher GHG emissions of the Res-REF.

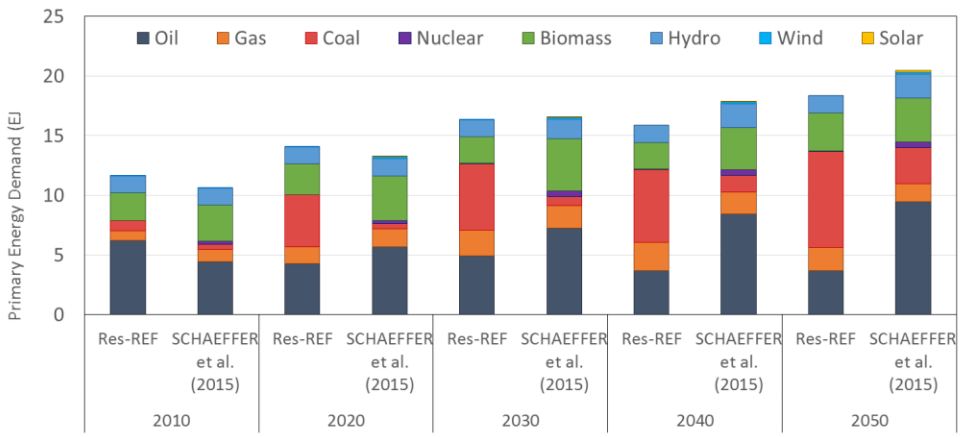


Figure 7-16 – Literature comparison of Brazilian primary energy demand (EJ)

Source: GEF from Schaeffer *et al.* (2015)

It is worth noting that the early increase in coal use in the Brazilian energy system in Res-REF is definitely larger than in SCHAEFFER *et al.* (2015). One of the main reason is the competitiveness of coal, as a cheaper energy source that can be economically transferred even from very long distances.

However, another major issue dealt within MESSAGE-Brazil (SCHAEFFER *et al.*, 2015) is the limitations of increasing imports of coal (and other energy products) due to the need for investment in new port capacity. In the model developed in this study, there is no such constrains to energy transfer, therefore coal becomes a cheap and easily available energy source.

7.3.RCP8.5 Scenario (Res-RCP85)

Since the Reference (Res-REF) scenario achieved total GHG emissions below the RCP 8.5 scenario for all years, there is no need to evaluate this case further. Thus, it can be inferred that, within this study, the SSP2 scenario is not compatible with the RCP 8.5, as some of the literature also suggest (KAINUMA *et al*., 2011; KRIEGLER, *et al*., 2012; PEREZ *et al*., 2014).

7.4.RCP6.0 Scenario (Res-RCP60)

7.4.1. GHG Emissions

The estimated global GHG emissions for the Res-RCP60 are presented in Figure 7-17. The land-related emissions remain positive and relatively low after 2030 until 2100. On the other hand, the energy-related emissions increase almost linearly until 2080 and drops rapidly afterwards.

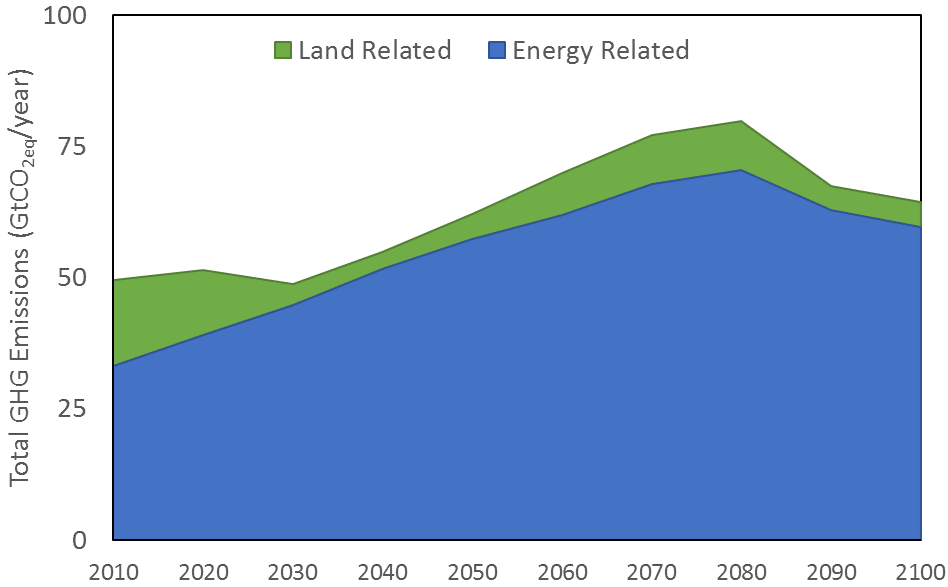


Figure 7-17 – Res-RCP60 GHG emission

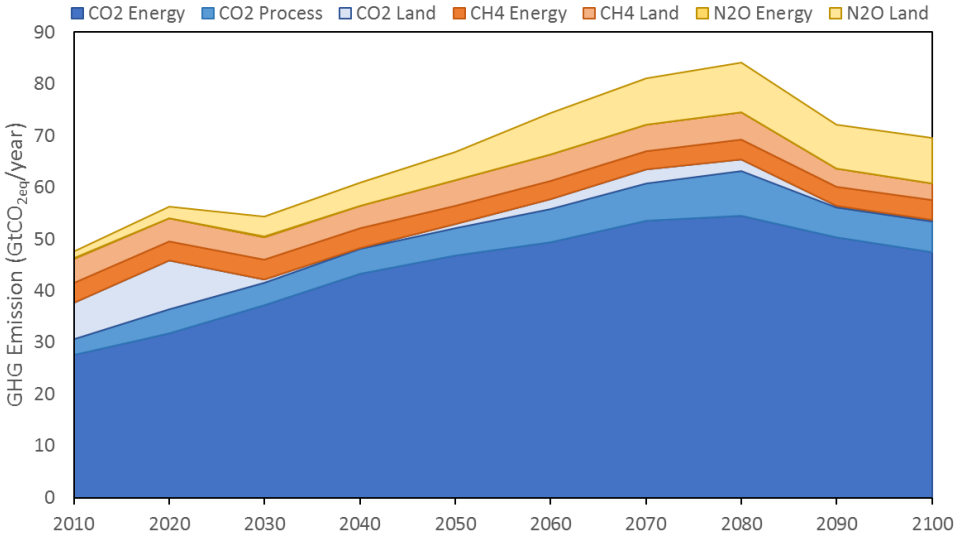


Figure 7-18 – Res-RCP60 GHG emissions by pollutant and source

7.4.2. Land Use and Land Use Change

This section explores the results for the global land system in the Res-RCP60. The results for land cover and land cover change are presented in Figure 7-19 and Figure 7-20, respectively.

The total cumulative land cover change in 2100 is of about 0.5 Gha, or about 4.3% of the total land surface of the world. Despite the higher land cover change than in the Reference scenario, the land-related emissions caused by land cover change are lower

than in Res-REF. The main reason for this is that global deforestation in Res-RCP60 is 31% lower than in the Res-REF scenario.

On the other hand, the transition of land cover between Forest and Grassland (For-Grass) is the main loser of land cover, with Grasslands following close behind. As in the Res-REF scenario, almost all of the land cover change cumulates towards cropland area until 2100.

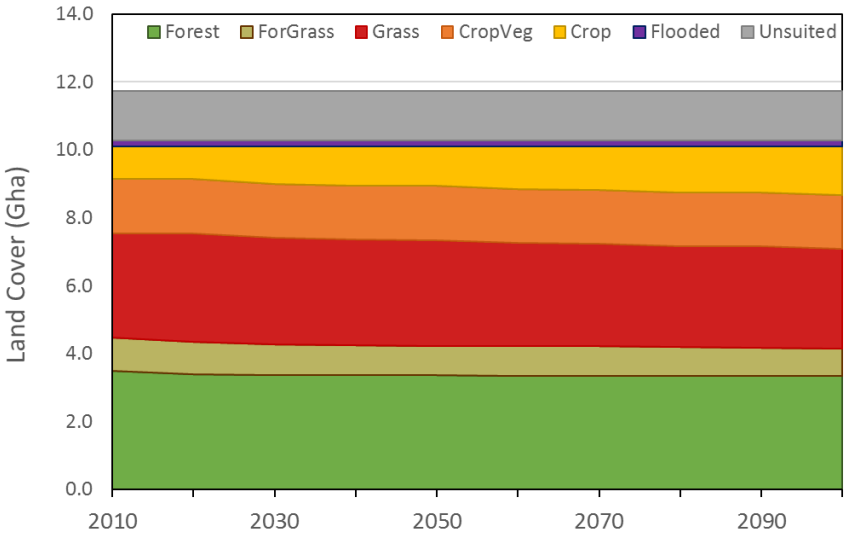


Figure 7-19 – Land cover for Res-RCP60

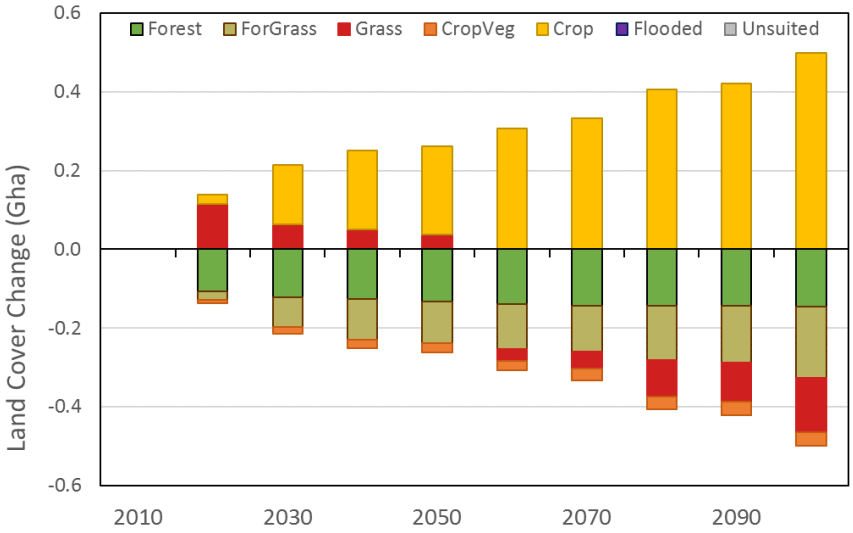


Figure 7-20 – Detailed cumulative land cover change for Res-RCP60

7.4.3. Primary Energy

This section explores the results for the energy system in the Res-RCP60 scenario. The total primary energy demand in 2100 is only slightly less than 2% higher than in the Res-REF scenario, but the breakdown is slightly different. In this scenario, coal, natural gas and wind lose space to biomass, nuclear and solar energy. Interestingly, oil demand increases about 2% in 2100 relative to the Reference scenario.

Despite the differences, the overall changes are relatively small compared to Res-REF, with the largest change attributed to nuclear energy, with about 25% higher primary energy consumption than in the Res-REF scenario, but still remaining the fourth most relevant energy source in the world in 2100.

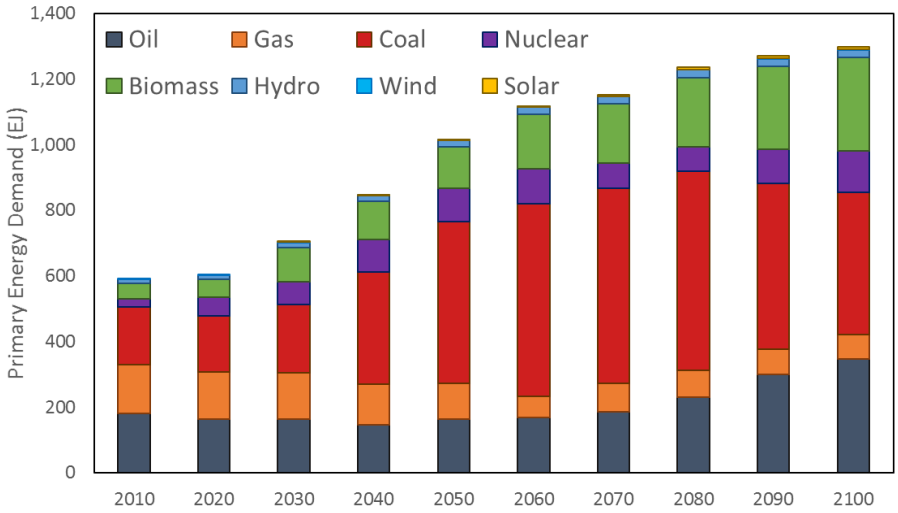


Figure 7-21 - Global primary energy demand (EJ) in Res-RCP60

Despite the energy portfolio being relatively close to the Res-REF, the main reason for the reduction of energy-related emissions are due to carbon capture and storage (CCS). The findings for global CCS are presented in Figure 7-22.

As can be observed, fossil-CCS rapidly increases after 2050, reaching about 1.5 $GtCO_2$/year captured. On the other hand, bioenergy-CCS (BECCS or BioCCS) starts relatively later but even faster than fossil-CCS, reaching almost the same 1.5 $GtCO_2$/year captured in 2100.

As discussed in previous sections, BECCS can achieve negative emissions, whilst fossil-CCS, at most, decreases emissions from fossil energy to roughly 10% of the

original carbon content. Thus, BECCS are amongst the most effective technologies to heavily reduce GHG emissions in the energy system.

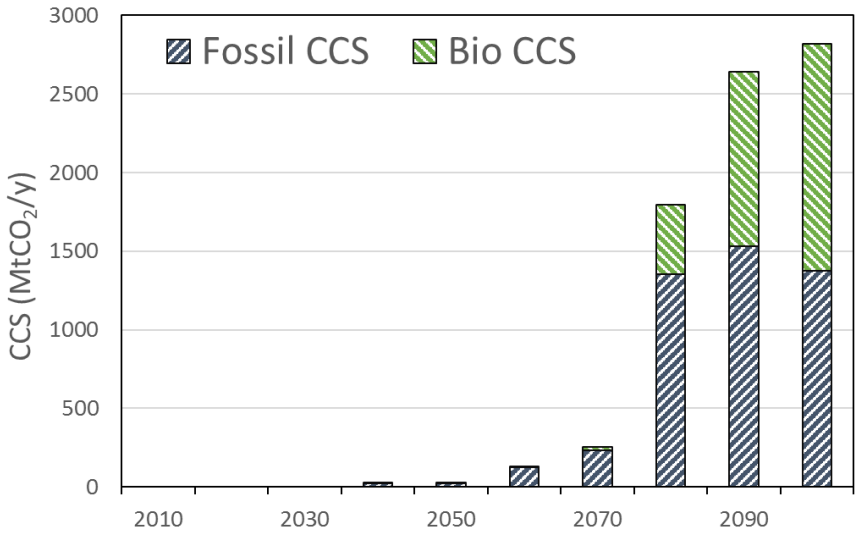


Figure 7-22 – Global fossil and Bioenergy CCS in Res-RCP60

7.4.4. Brazil

The global GHG emissions in the Res-RCP60 are already set by the profile of the RCP 6.0 itself. However, the breakdown of the global emissions profile into the 18 regions is an important result of this study. The role of a region in achieving global climate targets is determined by the mitigation opportunities, the relative competitiveness of the mitigation options and the regional socioeconomic development.

For Brazil, GHG emissions are presented in Figure 7-23 and Figure 7-24. The energy-related emissions continue to grow almost linearly until 2080, where they peak and drop in 2100. The total GHG emissions profile is relatively the same as the Res-REF until 2030, when it shifts towards a lower emissions profile. In 2070, a peak in land-related CO_2 emission causes the total GHG emission to overcome the Res-REF emission. This happens due to land cover changes into croplands, as will be discussed shortly.

In fact, the land system presents some interesting results. Another interesting fact is that methane emissions drop heavily after 2070, because the Brazilian cattle feedstock plunges, turning the country into a net importer of bovine meat, importing roughly 30% of the total demand for meat. Thus, other regions, such as East and West Europe (EEU

and WEU), become major exporters of meat with high production intensity and, therefore, lower methane emissions.

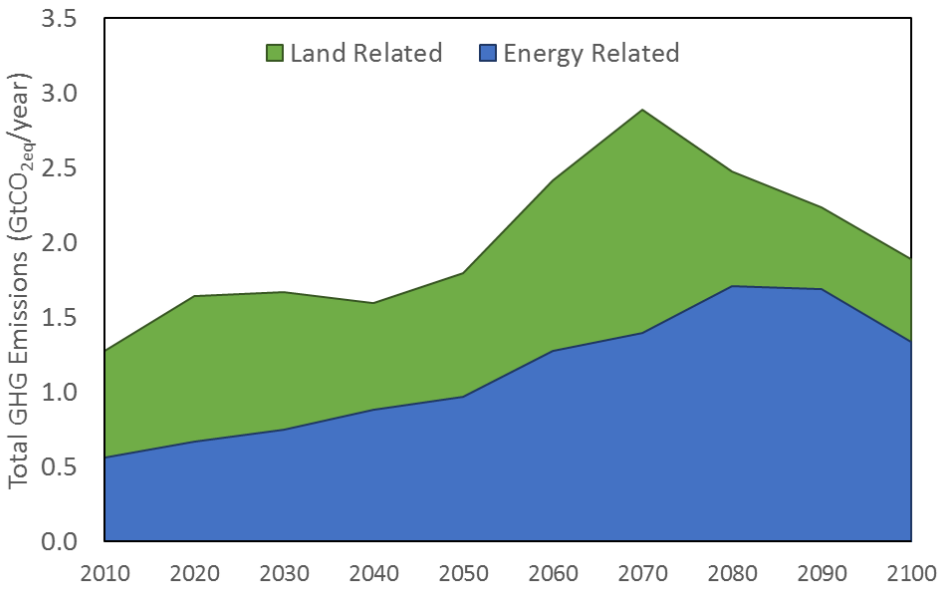


Figure 7-23 - Res-RCP60-BRA GHG-emission

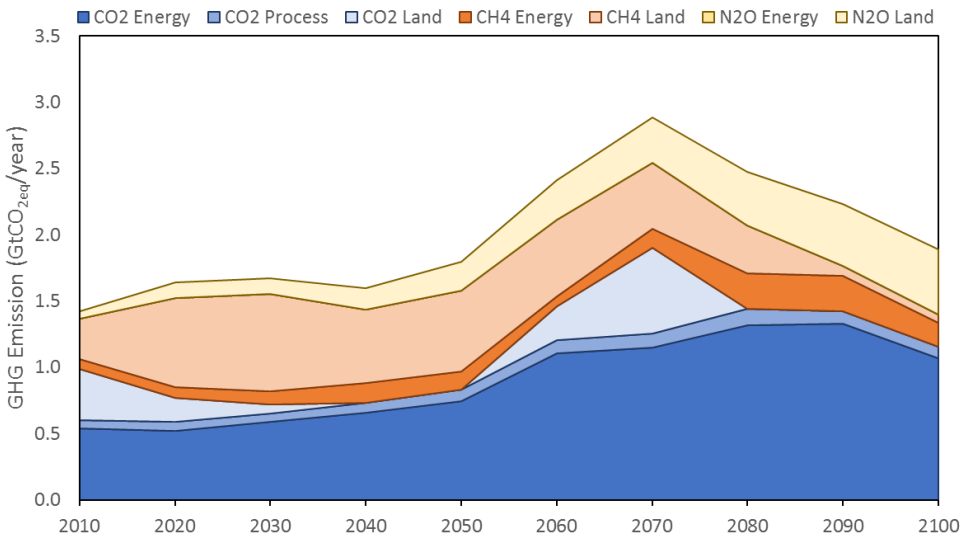


Figure 7-24 – Res-RCP60-BRA GHG-emission by pollutant and source

The land use change is reflected by the land cover change, as presented in Figure 7-25 and Figure 7-26. Deforestation happens in the beginning of the scenario, being the related land cover converted to grasslands, mostly for cattle. However, after 2070 grasslands start to shift towards croplands, increasing the Brazilian crop production, specially soybeans.

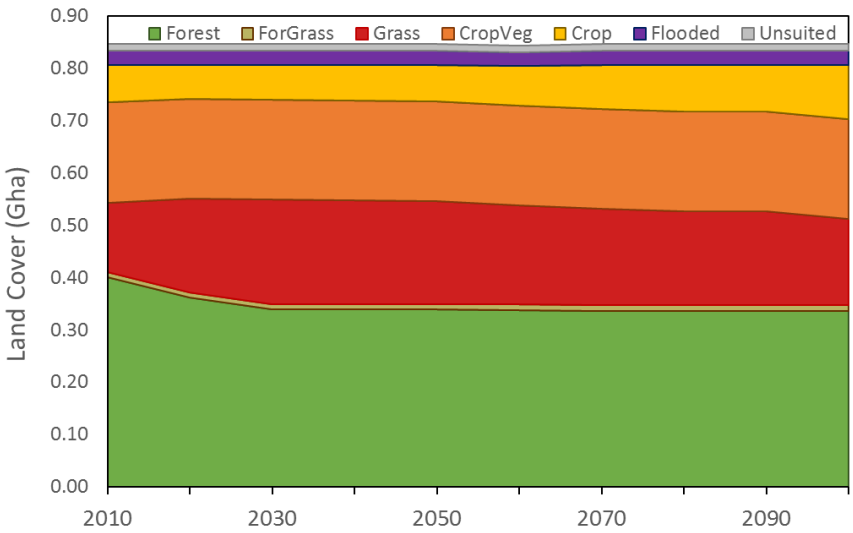


Figure 7-25 – Brazil land cover for Res-RCP60

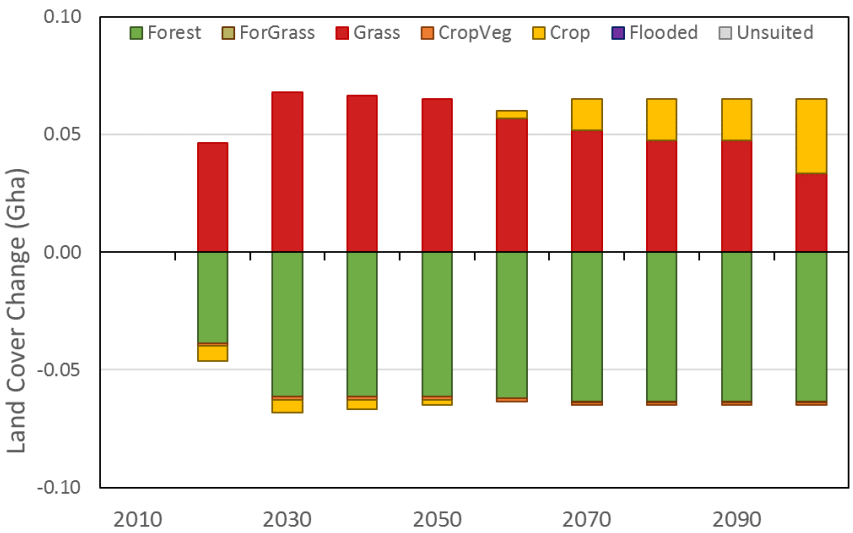


Figure 7-26 – Detailed cumulative Brazilian land cover change for Res-RCP60

As for the Brazilian energy system, results show a 6% lower demand of primary energy than in the Res-REF scenario. Also, there is a significant reduction in coal use, almost 41% related to the Res-REF consumption in 2100. Also, oil and biomass use increases 19% each. However, in this scenario, bioenergy becomes the most relevant energy source after 2080.

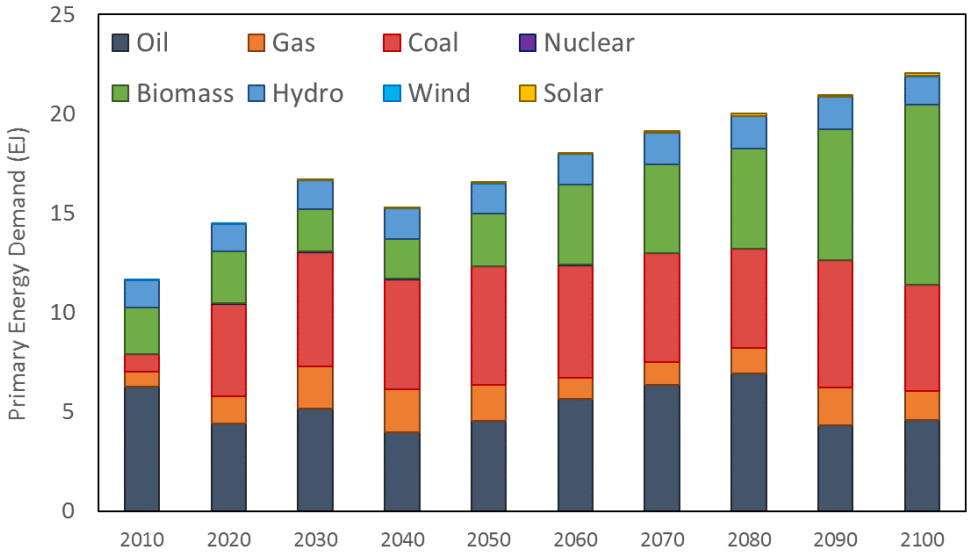


Figure 7-27 – Brazilian primary energy demand (EJ) in Res-RCP60

This is partially explained by the results in Figure 7-28, which presents the results for CCS in Brazil. The findings show that, for Brazil, BioCCS is largely more relevant than fossil CCS. However, BioCCS is only largely deployed in 2100, at a scale of about 130 $MtCO_2$/year. In 2100, Brazil is the largest user of BioCCS in the world, followed by Central and South America (CAM and SAM).

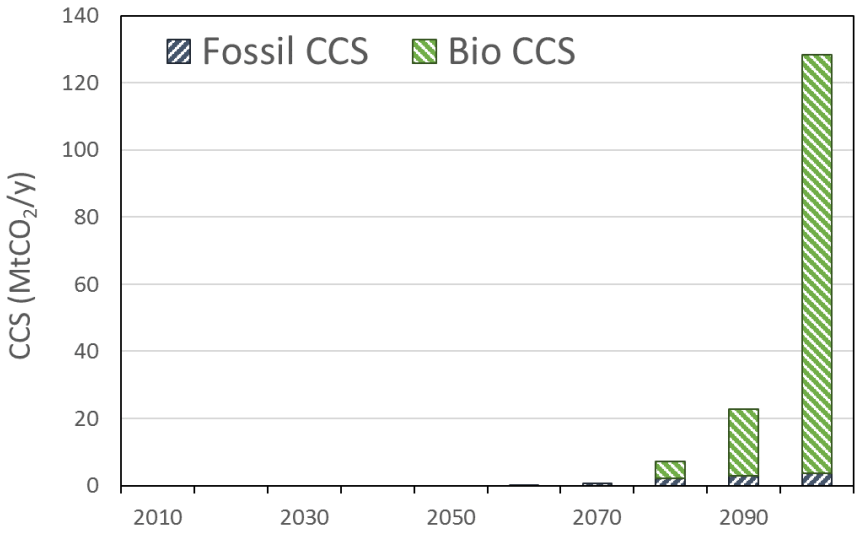


Figure 7-28 - Fossil and Bioenergy CCS in Brazil in Res-RCP60

7.5.RCP 4.5 Scenario (Res-RCP45)

7.5.1. GHG Emissions

The estimated global GHG emissions for the Res-RCP45 are presented in this section. Figure 7-29 shows that the land system presents net negative emission beyond 2070.

This becomes even clearer in Figure 7-30, where it shows that only CO_2 emissions of the land system are negative, whilst the other gases are responsible for positive emissions. Basically, this means that in, order to achieve the emission profile of the RCP 4.5, the model suggests that a positive balance of carbon stock in the above and below ground stocks due to land cover changes is necessary.

Besides, land cover change is a punctual source of negative emissions. Hence, in order to keep the total emissions at the target, additional land cover has to continuously keep changing. However, this process cannot continue indefinitely since there is a limited amount of land that can be transformed into higher carbon stock land covers.

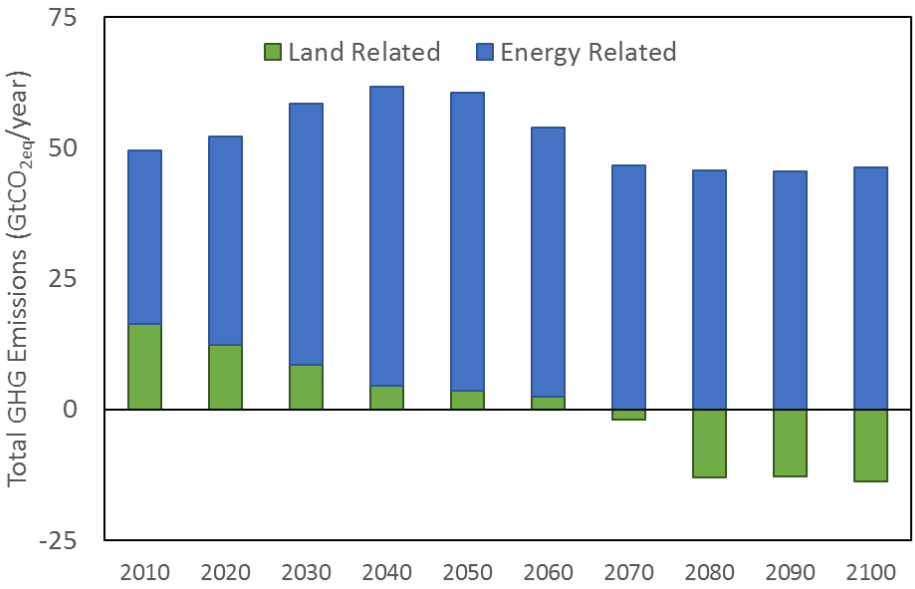


Figure 7-29 – Res-RCP45 GHG emission

As for the energy systems, the GHG emissions peaks at around 2050, and drops until 2070 when it stabilizes at around 46 $GtCO_{2eq}$. The profile is the same for all energy-related gases.

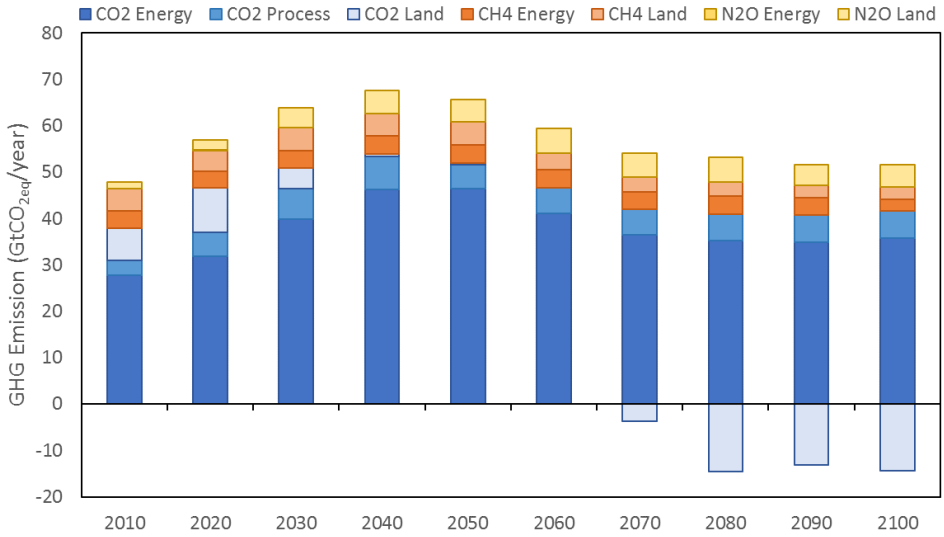


Figure 7-30 – Res-RCP45 GHG emissions by pollutant and source

7.5.2. Land Use and Land Use Change

The results for the global land cover in the Res-RCP60 are presented in Figure 7-31 and Figure 7-32. The total land cover change is of about 0.9 Gha, or about 8% of total land cover. As it happened in Res-RCP60, the larger land cover change is actually related to lower land emissions.

For instance, in this scenario deforestation plays a small role until 2030. However, afforestation partially restores the forest areas of the world from 2070 to 2100. The overall change for Forest cover is a 5% negative. The largest loser of land cover is Grasslands and For-Grass. Meanwhile, the main winner is, again, croplands, for which the additional croplands (related to Res-RCP60) are intensively used for bioenergy crops.

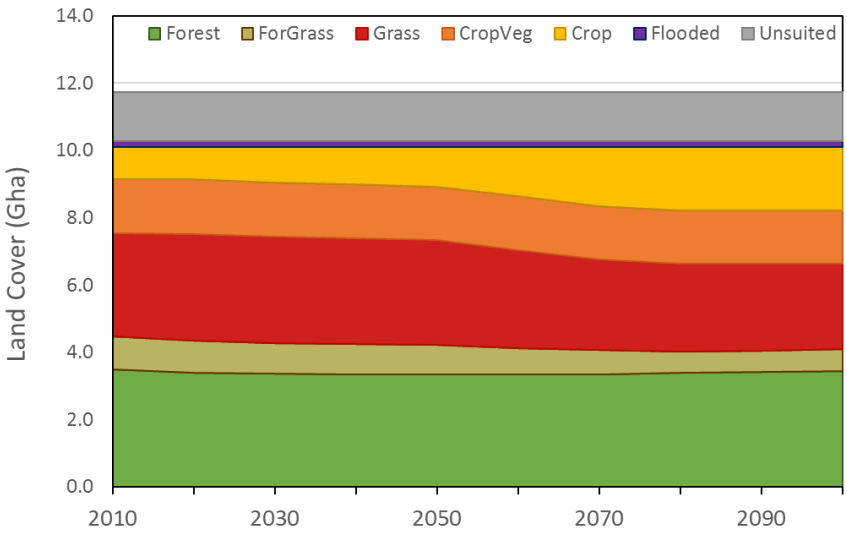


Figure 7-31 – Land cover for Res-RCP60

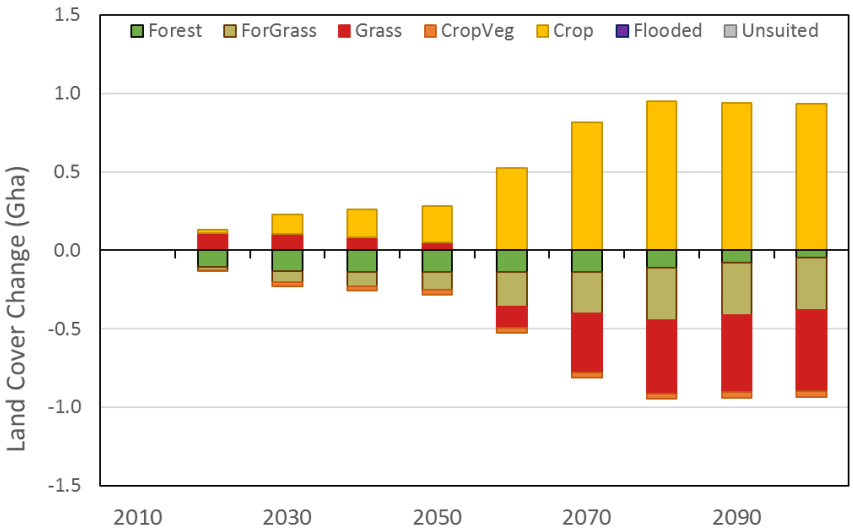


Figure 7-32 – Detailed cumulative land cover change for Res-RCP45

7.5.3. Primary Energy

This section explores the results for the energy system in the Res-RCP45 scenario. The shift from RCP 6.0 to RCP 4.5 intensifies the same effects of the shift from the Reference scenario to RCP 6.0.

Basically, the primary energy demand in Res-RCP4.5 is 4% higher than in Res-REF60, mostly due to the higher penetration of bioenergy, which usually has a lower efficiency than fossil fuels, and the energy penalty related to carbon capture and storage. Coal and natural gas continue to lose importance in the energy mix towards bioenergy,

nuclear and solar energy. These energy sources increase almost 10%, 51% and 64%, respectively. Nonetheless, coal remains the most important energy source, closely followed by oil and biomass.

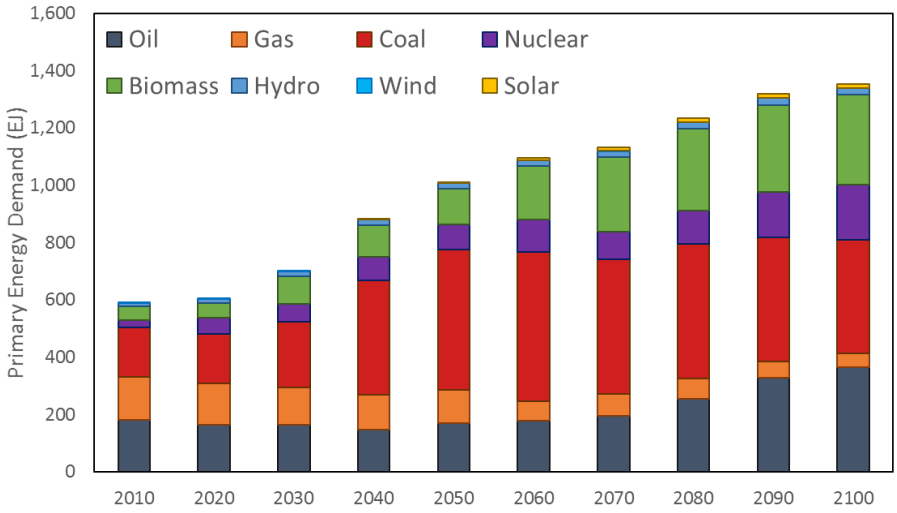


Figure 7-33 - Global primary energy demand (EJ) in Res-RCP45

As expected, CCS plays a larger role in the RCP 4.5 scenario, as shown in Figure 7-34. In fact, in 2100 the fossil and bioenergy CCS are almost 2.5 and 3.0 times larger, respectively, than in the RCP 6.0. Once again, BioCCS plays a larger role than fossil CCS in the end of the century.

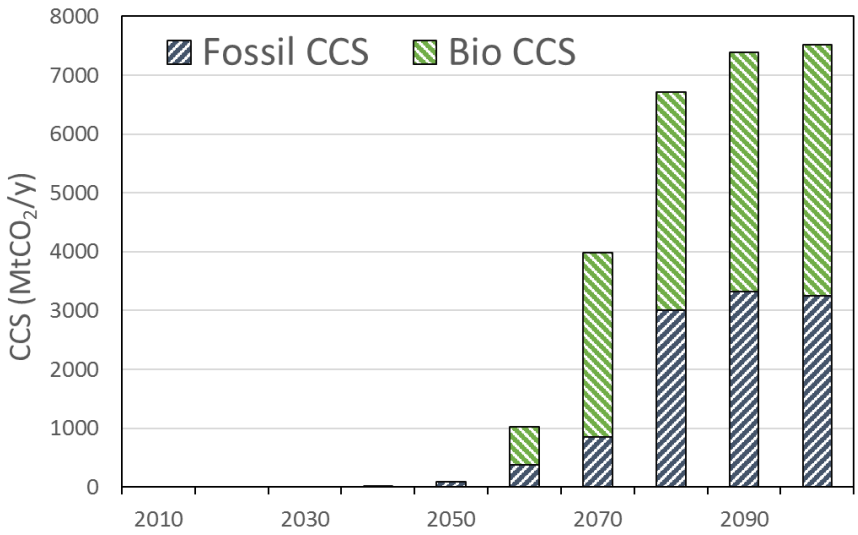


Figure 7-34 – Global fossil and Bioenergy CCS in Res-RCP45

7.5.4. Brazil

The GHG emissions for Brazil are presented in Figure 7-35. In the Res-RCP45, the Brazilian energy-related emissions continue to grow until 2100, with a little decrease between 2060 and 2080. This behaviour can be better understood by following the individual contribution of each GHG in Figure 7-36.

The energy-related CO_2 emissions increase linearly until 2100, with a minor additional peak in 2060, and the methane emissions increase after 2080 due to coal extraction.

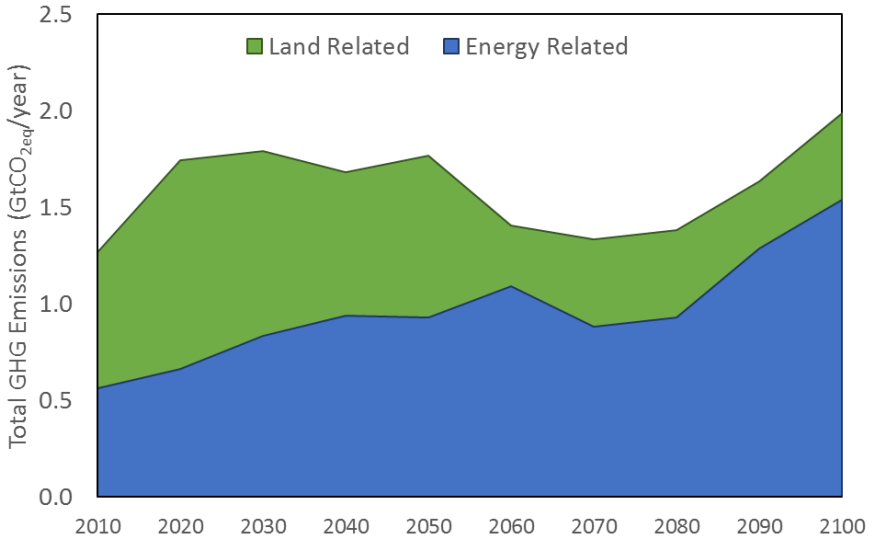


Figure 7-35 - Res-RCP45-BRA GHG-emission

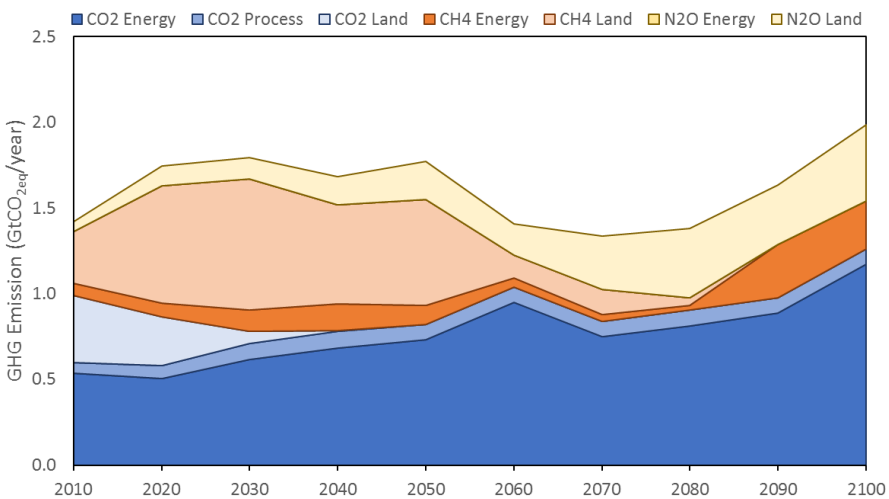


Figure 7-36 – Res-RCP45-BRA GHG-emission by pollutant and source

As for the land system, the behaviour presented for livestock in Res-REF45 is the same. Ergo, the cattle livestock drops after 2080, turning Brazil into a net importer of bovine meat. On the other hand, crop production increases after 2070 due to land cover change from grasslands to croplands. This behaviour can be seen in Figure 7-37 and Figure 7-38.

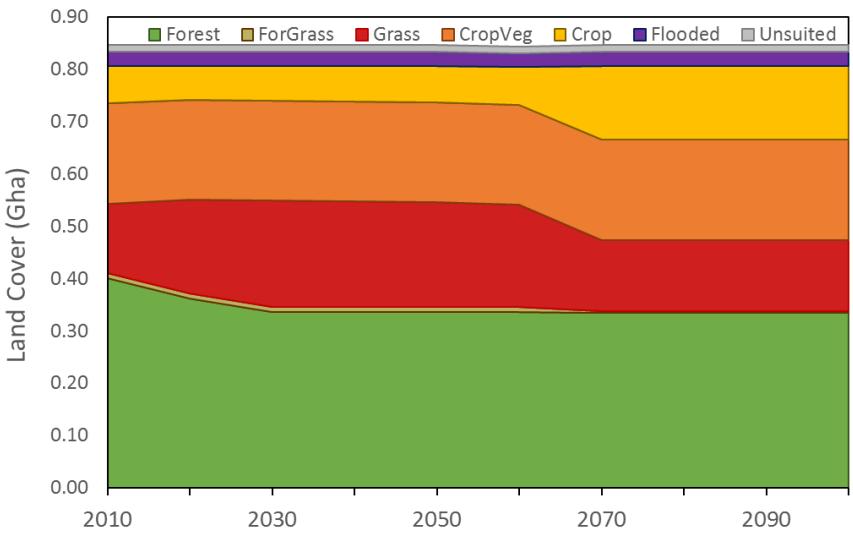


Figure 7-37 – Brazil land cover for Res-RCP45

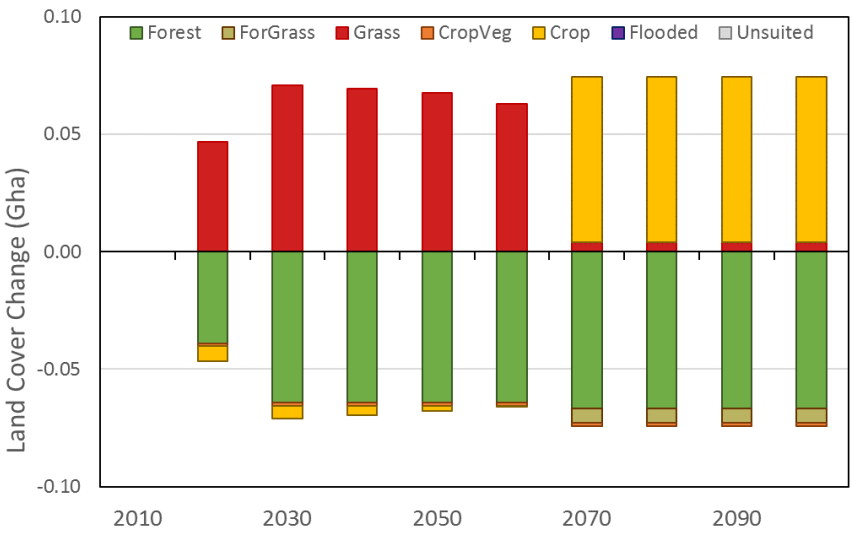


Figure 7-38 – Detailed cumulative Brazilian land cover change for Res-RCP45

The Brazilian primary energy demand under the RCP 4.5 is closely the same as the Res-REF scenario. From 2030 to until 2090, coal is systematically replaced by biomass and oil. However, by 2100, coal comes back, particularly national coal, replacing most of the oil use in the end uses. BioCCS use is improved in Res_RCP45, as can be

seen in Figure 7-40. This CCS option starts to be deployed earlier than in Res-RCP60, and it increases its usage in 2100 by roughly 30%.

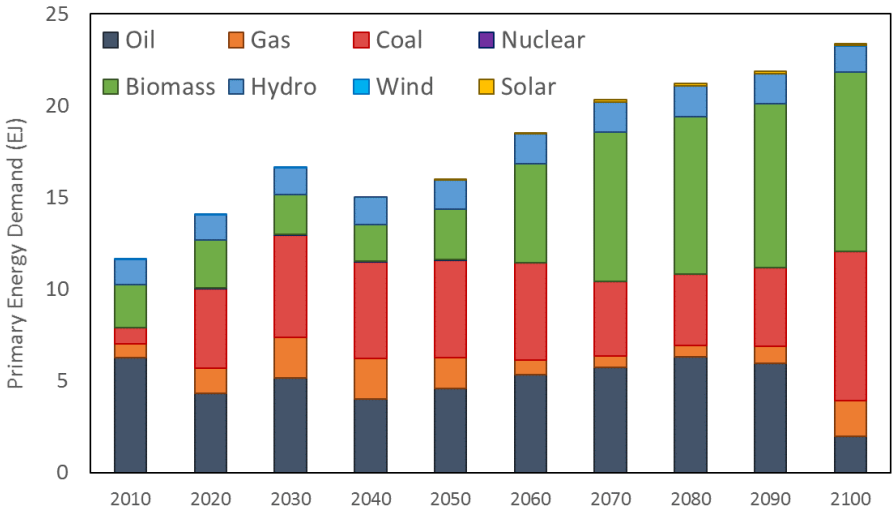


Figure 7-39 – Brazilian primary energy demand (EJ) in Res-RCP45

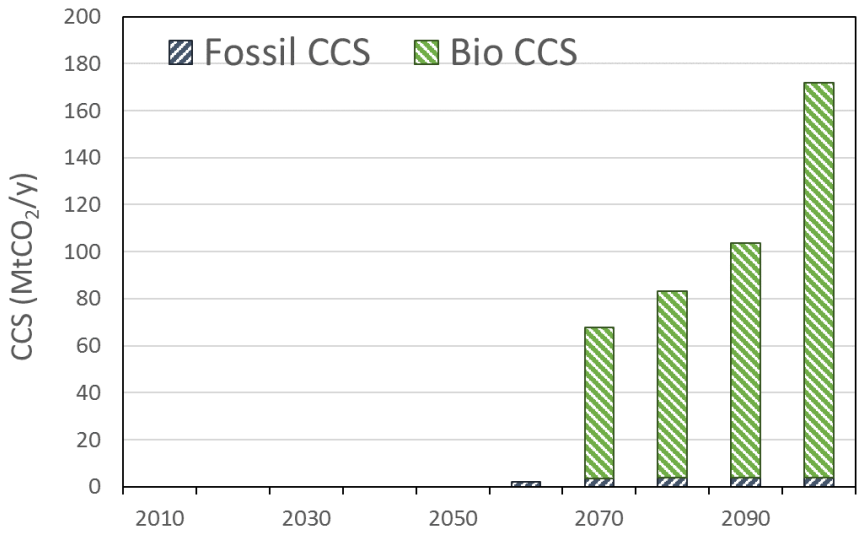


Figure 7-40 - Fossil and Bioenergy CCS in Brazil in Res-RCP45

7.6.RCP 2.6 Scenario (Res-RCP26)

7.6.1. GHG Emissions

In the Res-RCP26 the energy-related emissions present a "bouncing" behaviour, peaking at close to 31 $GtCO_{2eq}$ in 2030, then dropping to 23 $GtCO_{2eq}$ in 2050, only to increase again at roughly 0.9% per year until 2100. The land emissions decrease at an almost constant rate of 0.6 $GtCO_{2eq}$ per year, reaching net negative values as early as 2040. The complete profile of the global GHG emission is presented in Figure 7-41 and Figure 7-42.

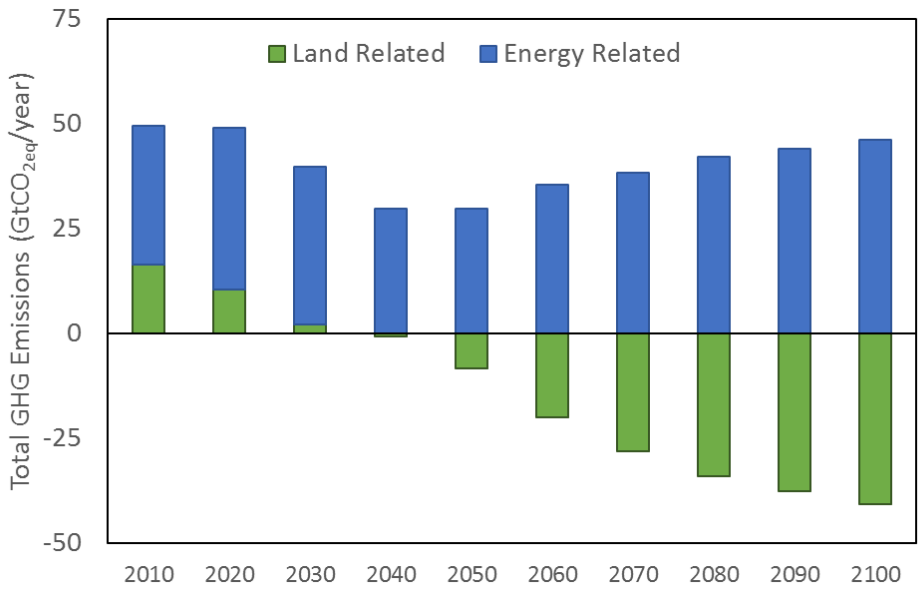


Figure 7-41 – Res-RCP26 GHG emission

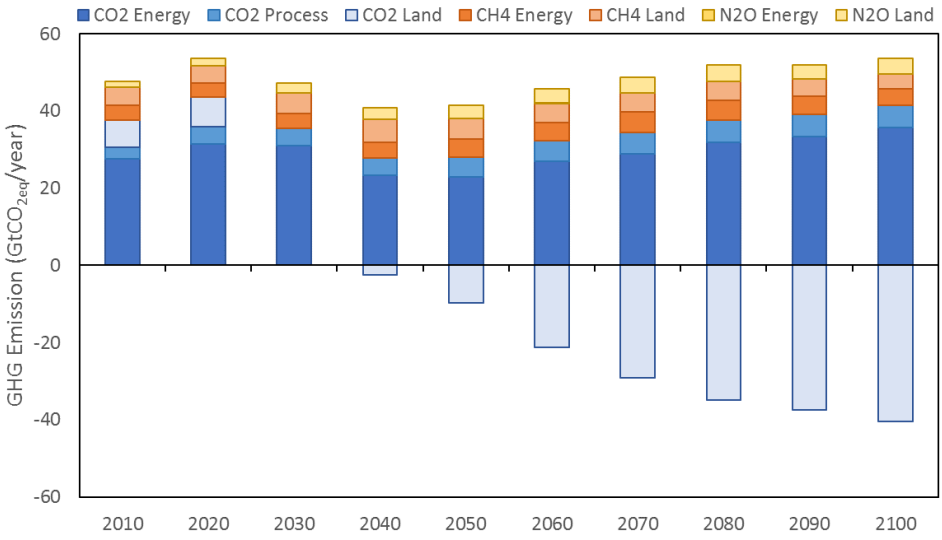


Figure 7-42 – Res-RCP26 GHG emissions by gas and source

7.6.2. Land Use and Land Use Change

The global land system within the RCP 2.6 presents a different profile than in previous scenarios. Firstly, the total cumulative land cover changes are of about 1 Gha, or roughly 9% of the total land cover of the world. Just as in the previous scenarios, the land cover that increases the most is cropland.

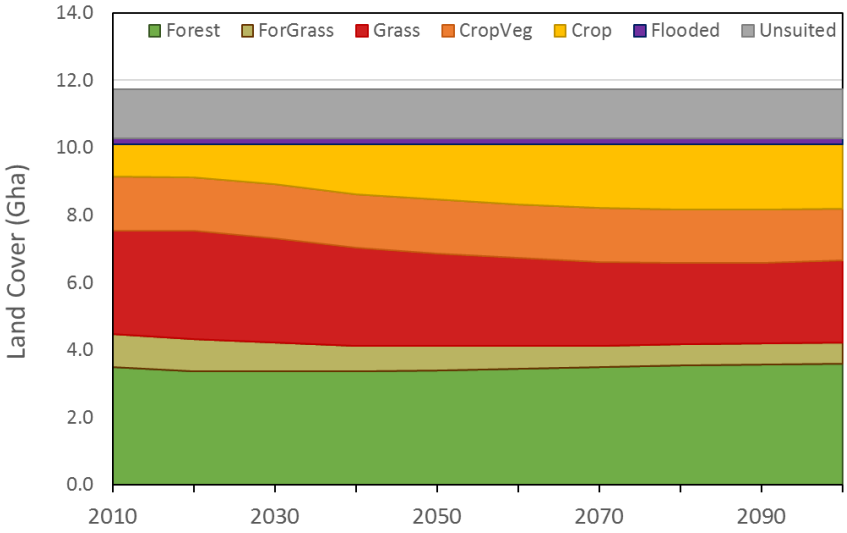


Figure 7-43 – Land cover for Res-RCP26

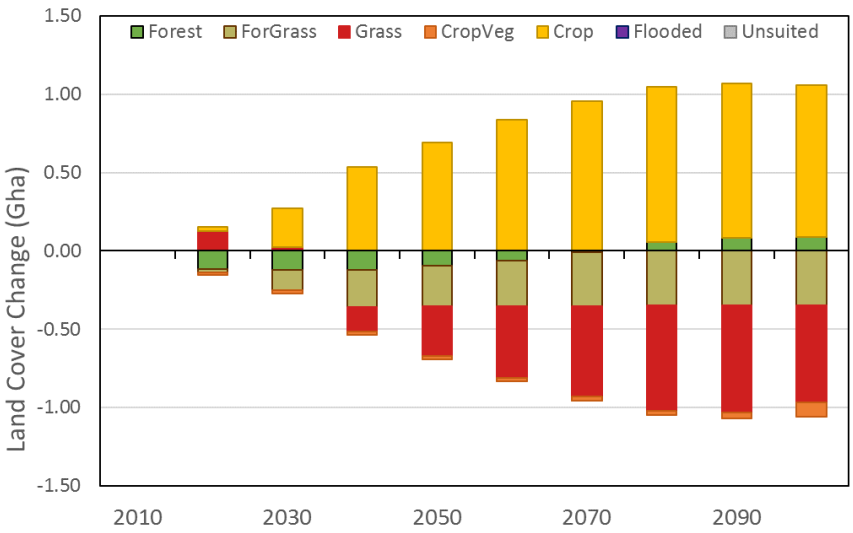


Figure 7-44 – Detailed cumulative land cover change for Res-RCP26

However, only this scenario presents a net positive change of land cover towards forest. As can be seen in both Figure 7-43 and Figure 7-44, up until 2030 the model suggests that deforestation towards croplands are relatively important. Nonetheless, until 2070 afforestation starts to compensate all the deforestation, ending up with additional forests areas in 2100 when compared to 2010. This is the main reason for the negative land-related emissions presented earlier.

7.6.3. Primary Energy

The primary energy in the Res-RCP26 in 2100 is extremely close to the Res-RCP45, not only in the total primary energy demand but also the profile of energy sources. However, the profile up until 2100 is completely different. The first difference is a significantly lower usage of coal up until 2070. For instance, in 2050 the use of coal related to the Res-RCP45 is 41% lower.

At the same year, oil and gas are about 10% lower than in Res-RCP45. Renewable energy sources and nuclear fuel are intensively used to compensate the lower use of fossil fuel. However, after 2070 the profile shifts towards the same as the Res-RCP45, but with a slightly lower primary energy demand (about 0.8%).

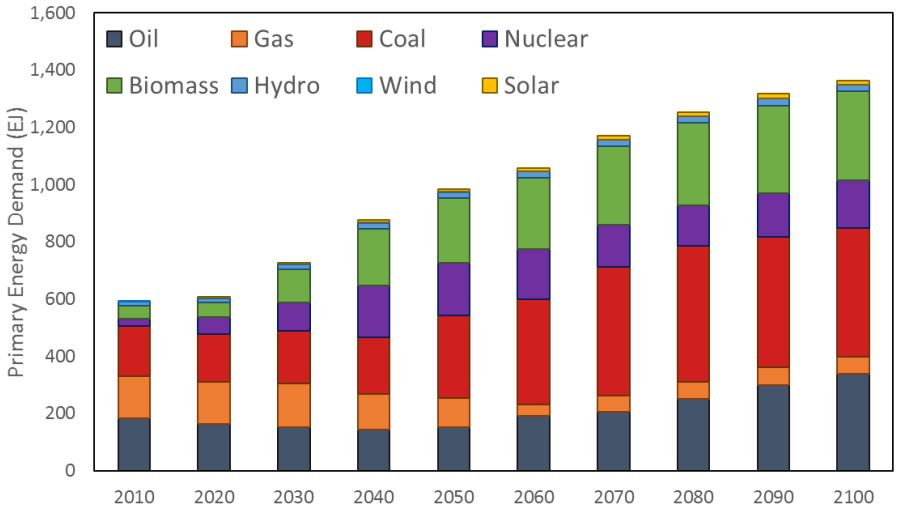


Figure 7-45 - Global primary energy demand (EJ) in Res-RCP26

More than ever, CCS is used to achieve lower emissions from the energy system. The results, presented in Figure 7-46, indicate that almost 9 $GtCO_{2eq}$ are captured in 2100, an increase of about 20% compared to Res-REF45. However, CCS deployment starts earlier, from 2030, whilst other scenarios started from 2070 onwards. BioCCS is extremely relevant up to 2070, when fossil and bioenergy are almost equivalent.

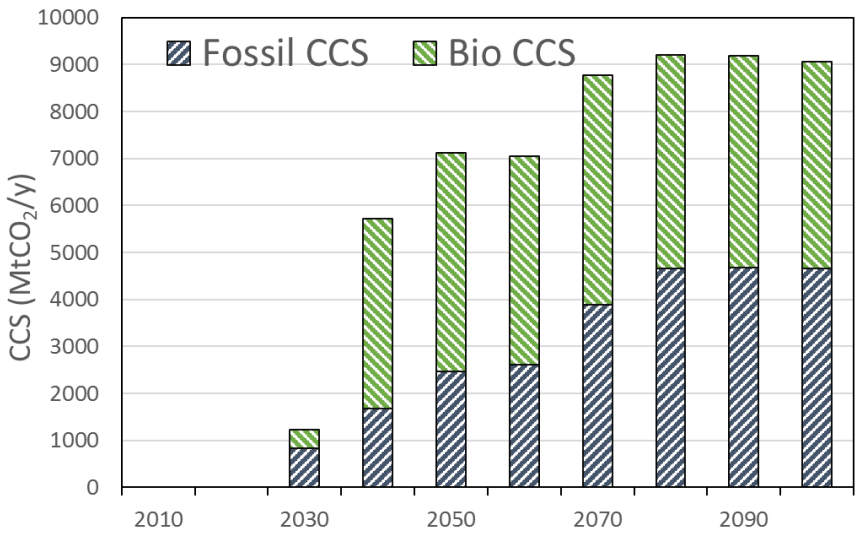


Figure 7-46 – Global fossil and Bioenergy CCS in Res-RCP26

7.6.4. Brazil

The Brazilian results for the RCP26 are presented in this section. First of all, the GHG emissions are presented in Figure 7-47and Figure 7-48. The energy-related emissions ranges from 0.60 and 0.65 $GtCO_{2eq}$ in the first half of the century and from 1.0 and 1.2 $GtCO_{2eq}$ on the second half of the century.

Nonetheless, the most relevant aspect of the Brazilian GHG emissions lies on the fact that land-related emissions become highly negative starting from 2070. Considering only CO_2, emissions from the land system are negative already in 2050.

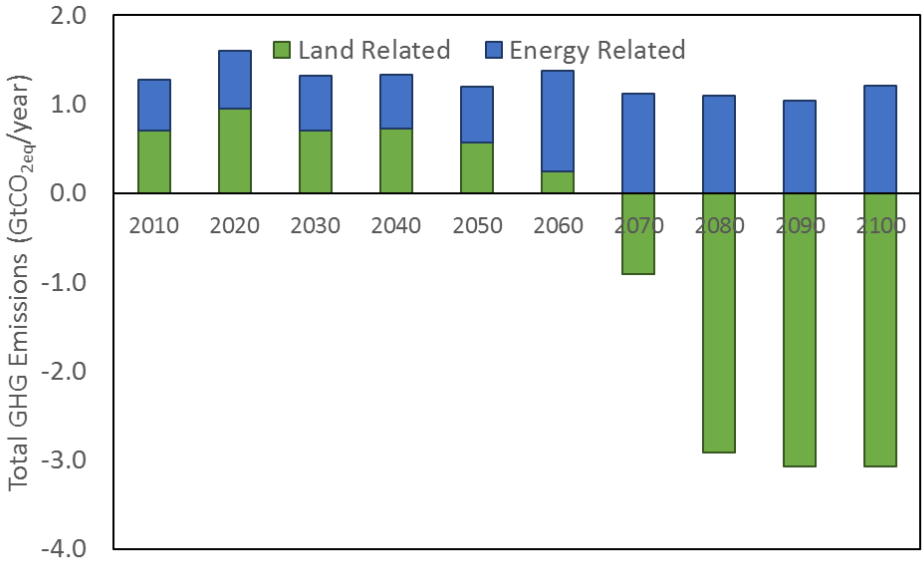


Figure 7-47 - Res-RCP26-BRA GHG-emission

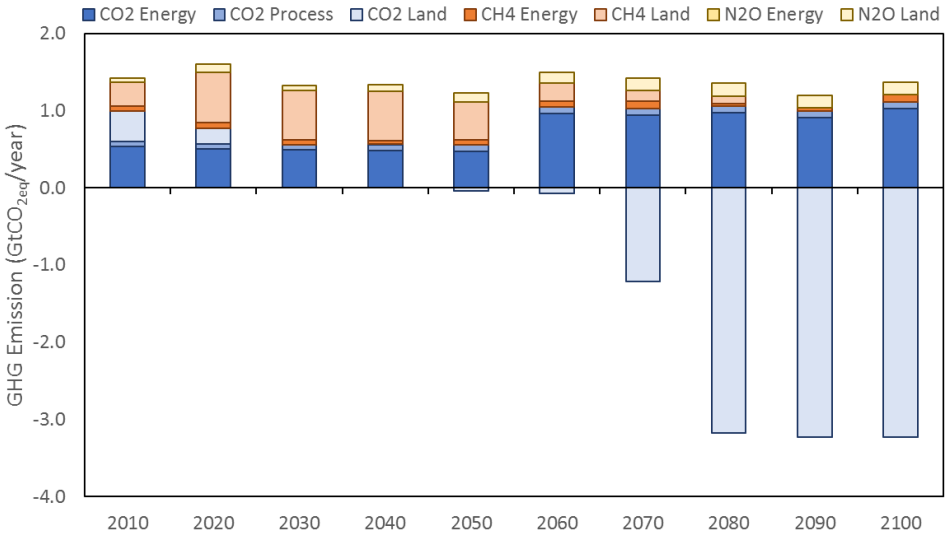


Figure 7-48 – Res-RCP26-BRA GHG-emission by pollutant and source

As for the Brazilian land system, the behaviour of the land cover is widely different in the two halves of the century. Figure 7-49 and Figure 7-50 show that in the first half of the century the overall land cover changes favour grasslands. However, starting from 2030 the land begins to shift towards crops, which dominates the second half of the century.

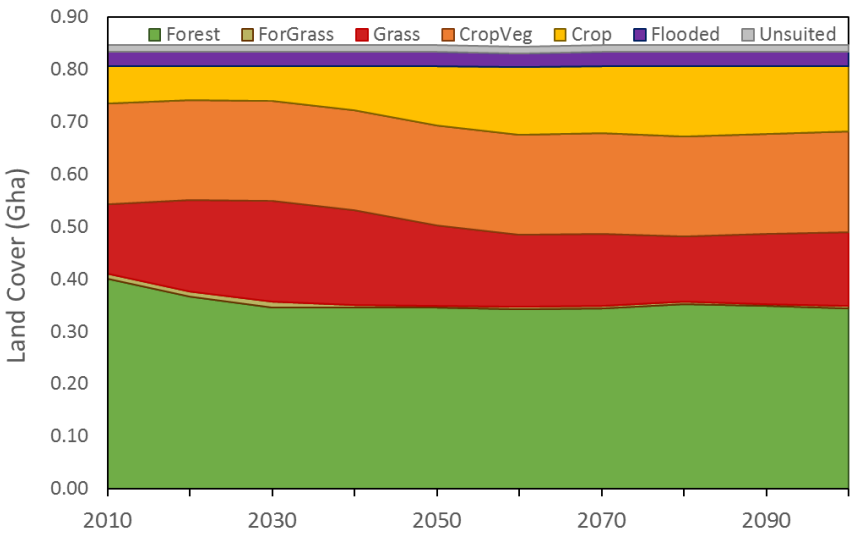


Figure 7-49 – Brazil land cover for Res-RCP26

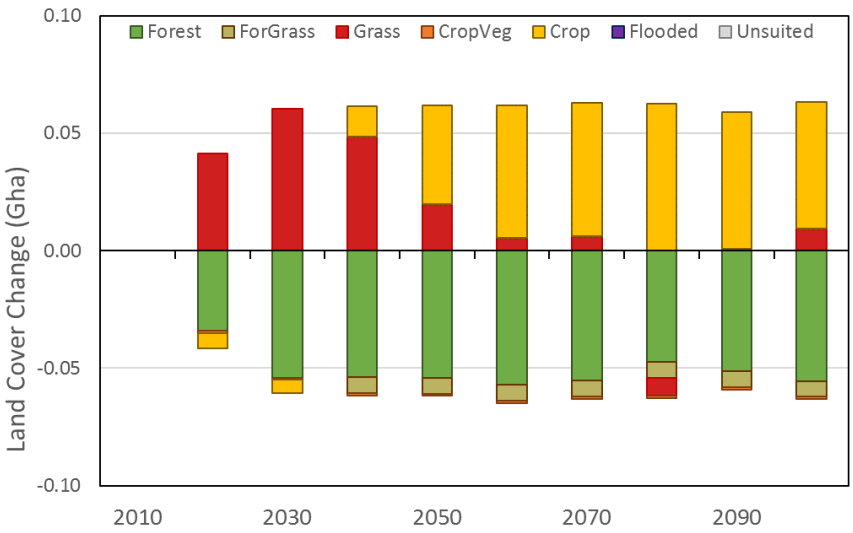


Figure 7-50 – Detailed cumulative Brazilian land cover change for Res-RCP26

The Brazilian energy system becomes even more dependent on bioenergy sources in this scenario, as presented in Figure 7-51. Coal use remains roughly constant after 2020, ranging from 4.5 to 5.5 EJ/year. Compared to the Res-RCP45, the energy sources whose usage increase the most are wind energy (almost 180% increase in 2100) and oil (with 150% increase in 2100).

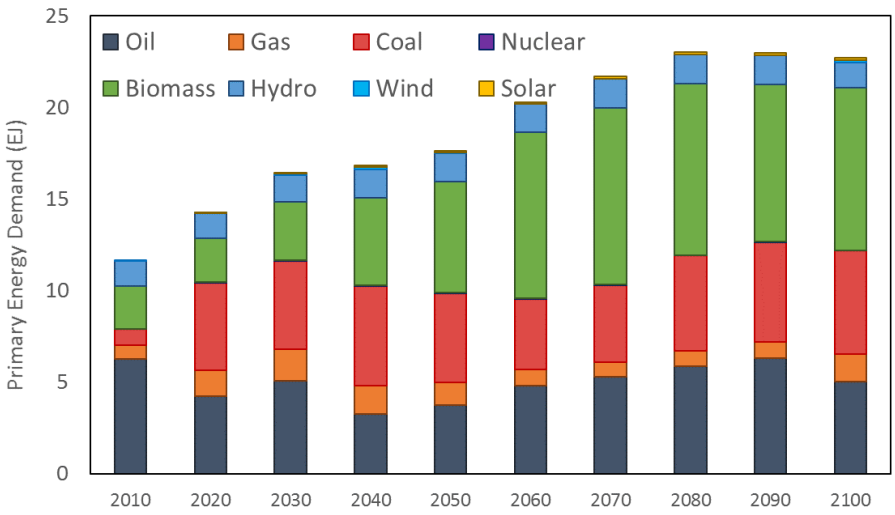


Figure 7-51 – Brazilian primary energy demand (EJ) in Res-RCP26

As for CCS, just as in the Res-RCP45, BioCCS becomes extremely relevant for the Brazilian energy system, compared to Fossil-CCS. However, just as for the global deployment of CCS in Res-RCP26, the use of CCS starts much earlier, as presented in

Figure 7-52. The total carbon captured in 2100 is equivalent to the Res-RCP45, but this value is reached as early as 2080.

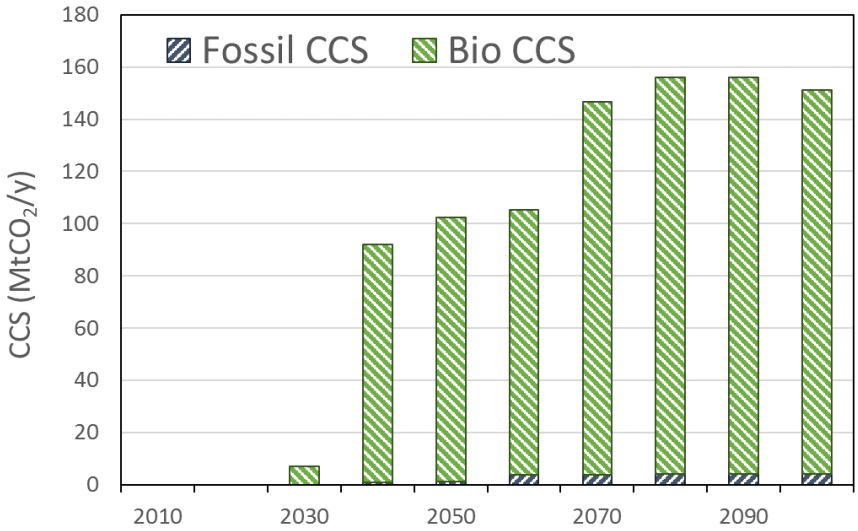


Figure 7-52 - Fossil and Bioenergy CCS in Brazil in Res-RCP26

7.7. Summary of the RCPs

In this section, the results of the scenario protocol are summarized. Thus, by comparing the results of each scenario their implications become clearer.

The first aspect to be assessed is GHG emissions, just as they were presented in the section for each scenario. Figure 7-5 already presented the relative profile of the four RCP scenarios and the Reference scenario obtained in this study.

Figure 7-53 presents the breakdown of total GHG emissions by system and pollutants, for each scenario. Interestingly, Res-REF and Res-RCP45 have almost the same emissions profile, whilst Res-RCP60 and Res-RCP26 have some similarities, even though the latter has lower emissions of energy-CO_2 and land-N_2O.

In 2050, only Res-RCP26 have a different emission profile (lower and with negative land-CO_2 emissions), whilst the other three are almost identical. In 2100, however, the emissions are widely different, as expected from the nature of each RCP.

Another interesting fact is that the emissions profile, disregarding land-CO_2, in Res-RCP4.5 and Res-RCP2.6 are remarkably the same. This suggests that the impact of the climate target on the energy system and land system is basically the same, or very similar.

At the same time, the land cover change is the main factor responsible for achieving either the RCP 4.5 and RCP 2.6. This also suggests that, for any scenario beyond 2100 the potential role of land cover change in reducing emissions could saturate and, therefore, the emissions profile of a world that achieved the RCP 2.6 until 2100 would be the same as the one that achieved a less stringent climate target. Thus, this would have repercussions towards climate change mitigation beyond 2100.

The results for the land cover change are presented in Figure 7-54. In the RCP 2.6 there is less deforestation, despite the additional cropland applied for bioenergy production. Only in the Res-RCP2.6 net positive changes towards forests (afforestation) are achieved.

Finally, the impacts on the energy system are summarized in Figure 7-55. The figure presents a similar profile in 2030 for all scenarios. In 2050, only the RCP 2.6 presents a significantly different profile, where bioenergy has a larger role in the energy mix, coal loses competitiveness, and there is a small additional use of nuclear and solar energy.

Interestingly, in 2100 the profile for primary energy demand is again very similar between scenarios, with small changes favouring nuclear, bioenergy and solar energy in Res-RCP45 and Res-RCP26. Findings also suggest that coal is able to keep a significant role in the energy mix due to the addition of carbon capture and storage.

The economic impact of harshly constraining GHG emissions can be assessed by the shadow price of GHG emissions, which can be provided by the linear programming model. In this context, the shadow price represents the internalization of the carbon cost to the energy and land systems. Thus, the higher the cost of carbon, the stronger it is the economic incentive to reduce carbon emissions.

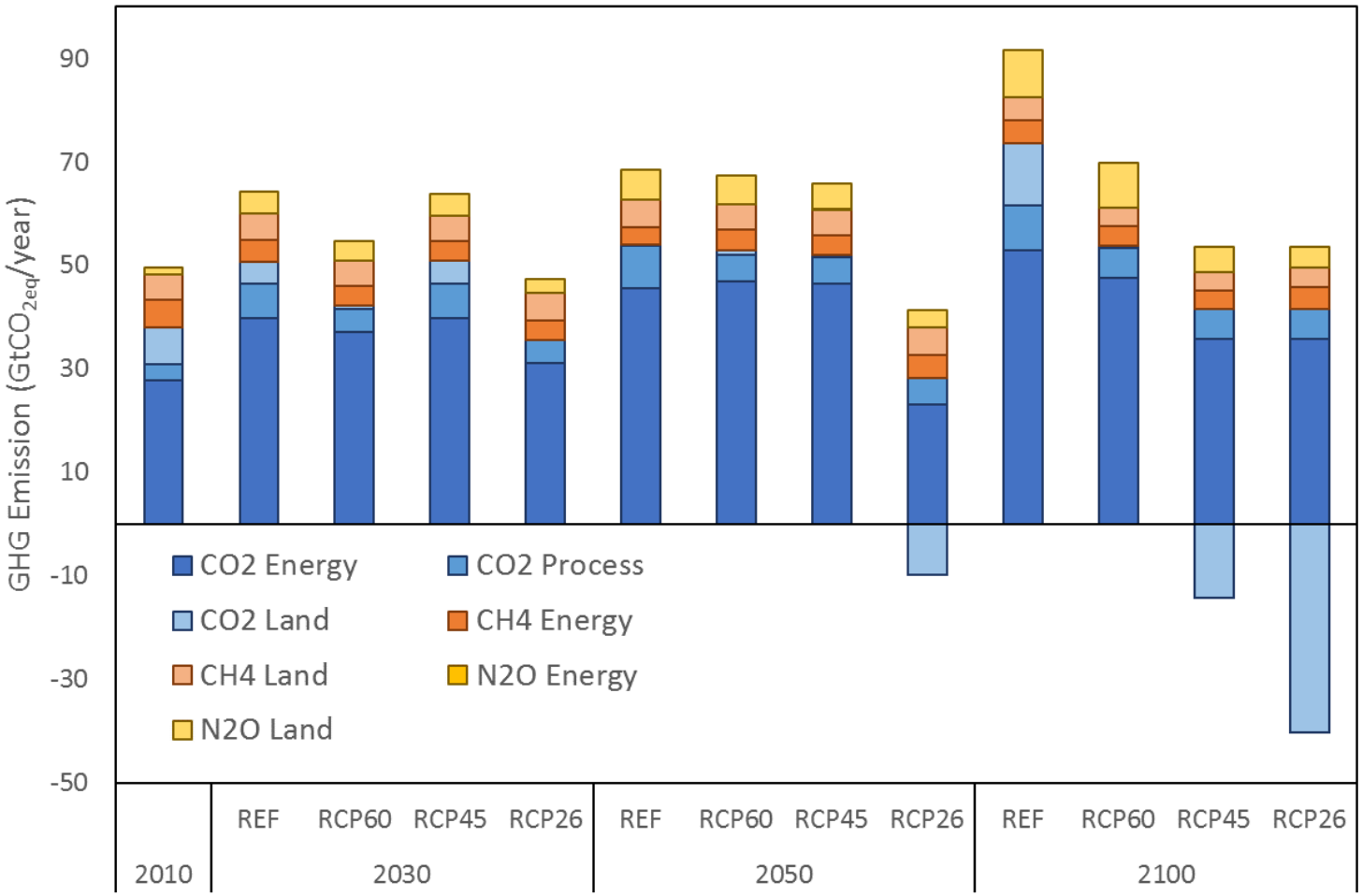


Figure 7-53 – Result summary of global GHG emissions ($MtCO_{2eq}$)

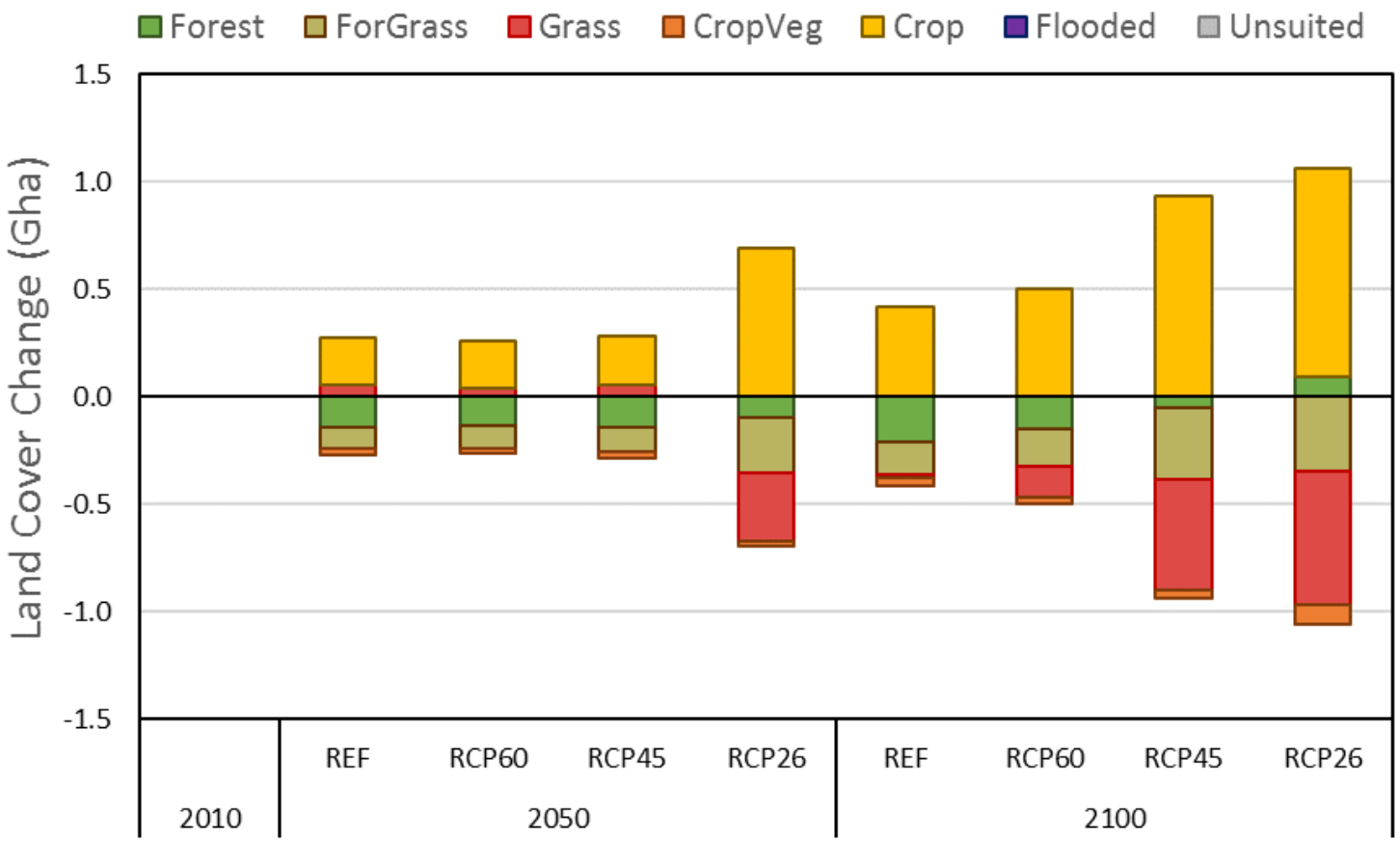


Figure 7-54 – Summary of global land cover changes (Gha)

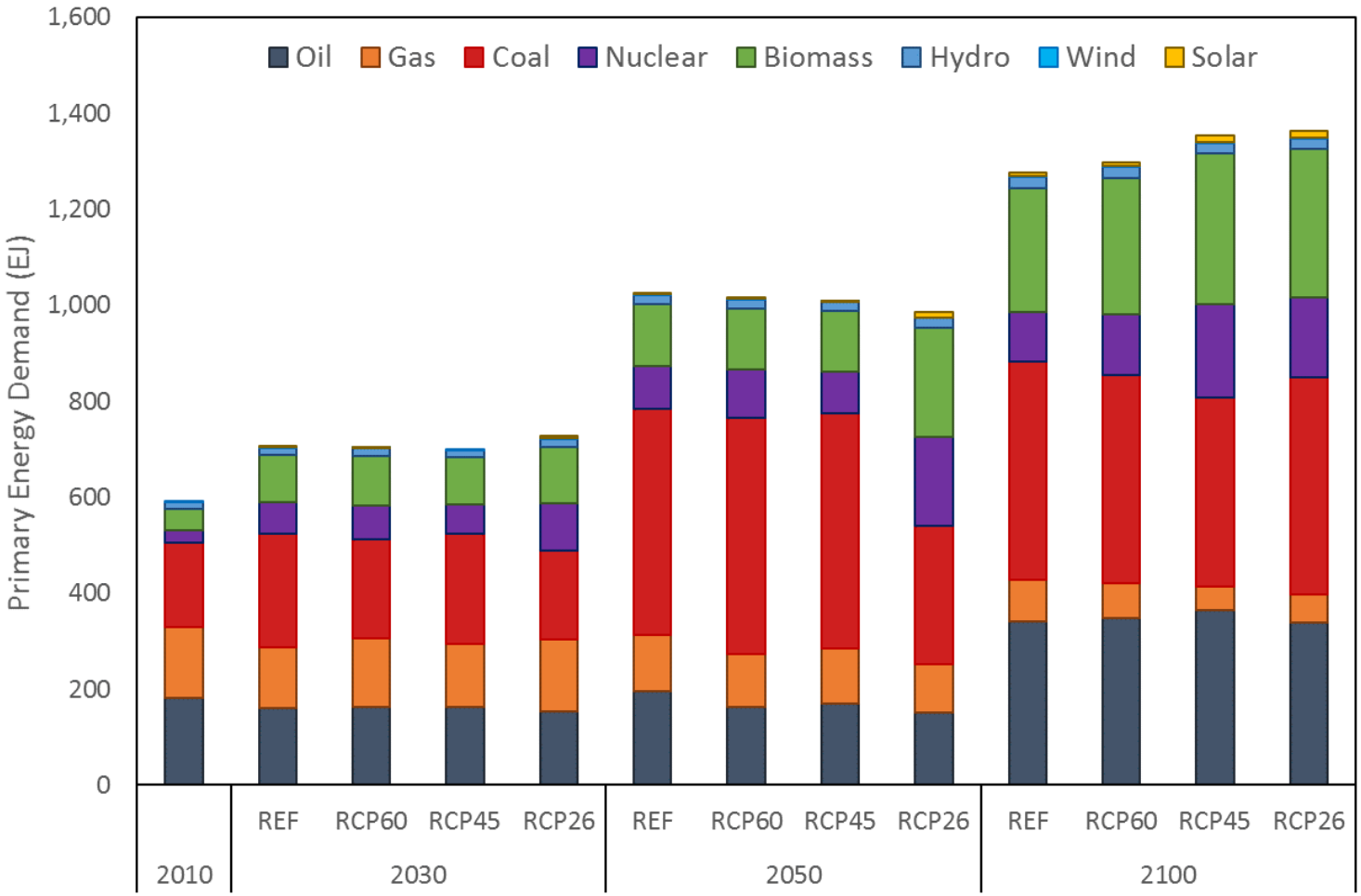


Figure 7-55 – Summary of global primary energy demand (EJ)

The results of this study for the shadow price of carbon emissions for each scenario are presented in Figure 7-56. Considering the overall profile of each cost curve, it can be stated that the scenarios with higher carbon constraints are directly related to a higher shadow price.

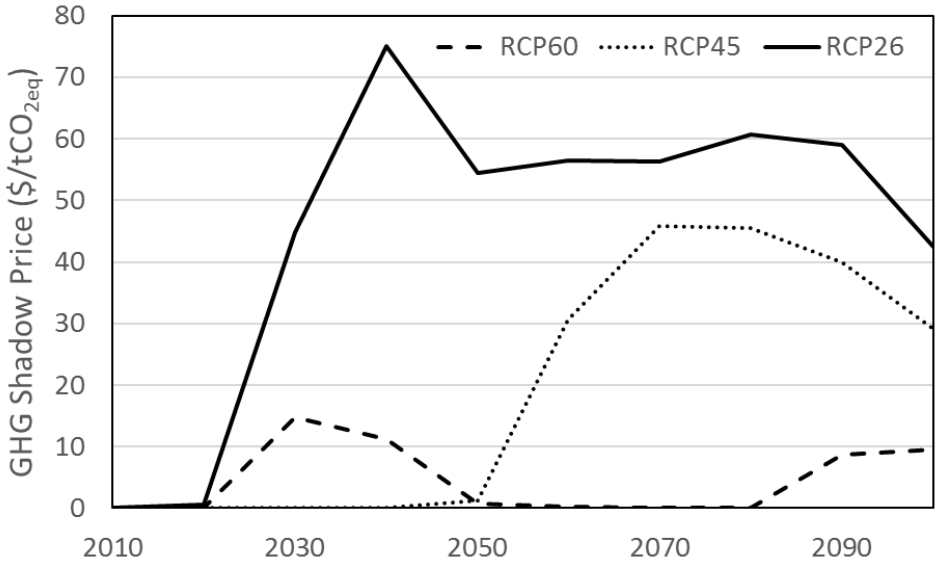


Figure 7-56 – Shadow price of GHG

The abnormal profile of each curve is a typical result of a linear programming optimization model. In this sense, there is no connection between the internal cost of carbon from one year to another. The only effect in place is the effort to achieve a particular emission constraint at a given year. As it can be seen, even in a more stringent scenario, there are periods when this effort is considerably larger.

In typical energy models coupled to economic models, such as CGE models, the profile is smoother and well behaved. Examples of such profiles are presented in Figure 7-57.

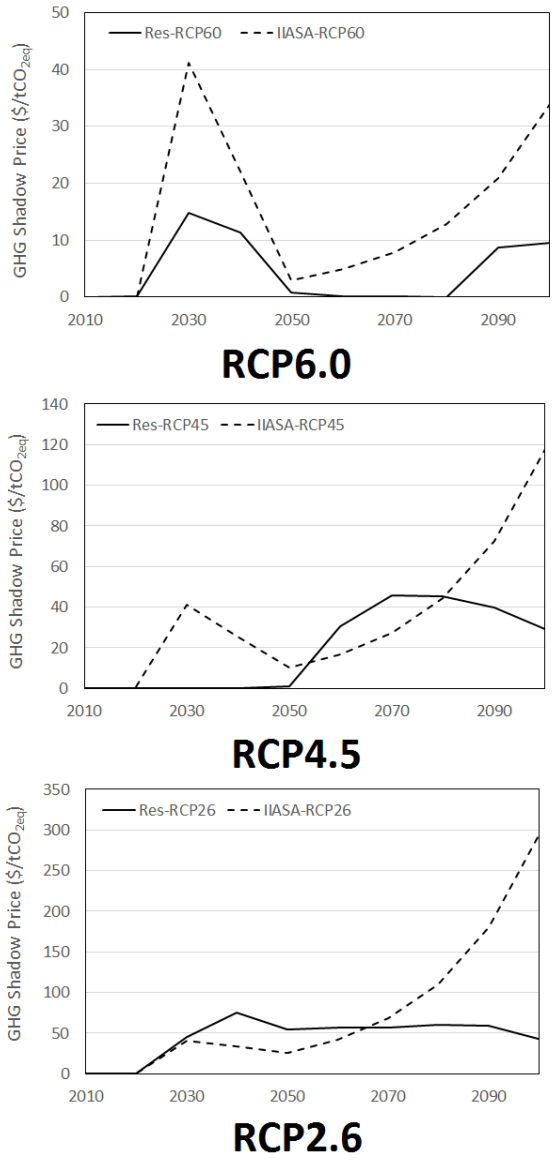


Figure 7-57 – Results of GHG Shadow price for each RCP

Source: data from IIASA, 2013b

The figure presents the results for each scenario in comparison to the data available in IIASA (2013b) for the SSP2 results. The results from IIASA present a perfect exponential growth of the carbon cost after 2050 for each scenario. Even though the results are not closely linked, they do share some similarities.

Thus, in order to assess the true effect of the GHG emission constraint in the economy, the model developed in this study should be coupled with a macroeconomic model. As already discussed, CGE models are amongst the preferred choice of the IAM community.

7.7.1. Implications for Brazil

This section explores the results of the scenario protocol focusing on the Brazilian part. Hence, the effects of achieving global climate targets on the Brazilian energy and land system will be assessed.

Following the same protocol for result analysis, GHG emissions will be addressed first. The summary of the results of the Brazilian GHG emissions under the scenario protocol is presented in Figure 7-58. The findings suggest that, in 2030, the emissions profile for Res-REF, Res-RCP60 and Res-RCP45 are relatively similar, whilst Res-RCP26 presents lower energy-CO_2 and land-N_2O emissions.

In 2050, the most opposed scenarios, Reference and RCP 2.6, have widely different emissions, as expected. However, both Res-RCP 6.0 and RCP 4.5 suggest the same emission intensity and profile.

This same behaviour is enhanced in 2100, where the discrepancies between Res-REF and Res-RCP26 are wider, but Res-RCP60 and Res-RCP45 remain fairly similar, with only small changes in methane emissions (shifting from land to energy).

Nonetheless, the most overwhelming fact in these results is the relatively high net negative emissions of CO_2 from the land system. The negative CO_2 emissions start in 2050, with barely negative emissions, but reach almost -3.5 $GtCO_2$ in 2100.

The results for cumulative land cover changes in the Brazilian land system are presented in Figure 7-59. Whilst there are consistent levels of deforestation in all scenarios, the objective of the land cover change varies throughout the scenarios.

Until 2050, with the exception of Res-RCP26, the land cover changes favour grasslands for increasing the cattle livestock and, consequently, the bovine meat production. However, after 2050 up until 2100 the land use changes from livestock to crop production, increasingly for scenarios with higher carbon constraints. For instance, in 2100 in Res-RCP45, the change towards grasslands increase this land cover by only 0.4% compared to 2010 values. Therefore, this is a marginally positive change for grasslands.

The effects of the scenario protocol on the Brazilian energy system are summarized in Figure 7-60. Despite the erratic behaviour of the primary energy demand, a general profile can be extracted from this figure. Systematically, bioenergy becomes more relevant, whilst fossil fuels keep the relative importance achieved by the half of the century.

The same can be said for Hydro energy, which hardly is affected between scenarios. Finally, new renewables and nuclear have some differences, but never reach significant levels of participation in the energy mix.

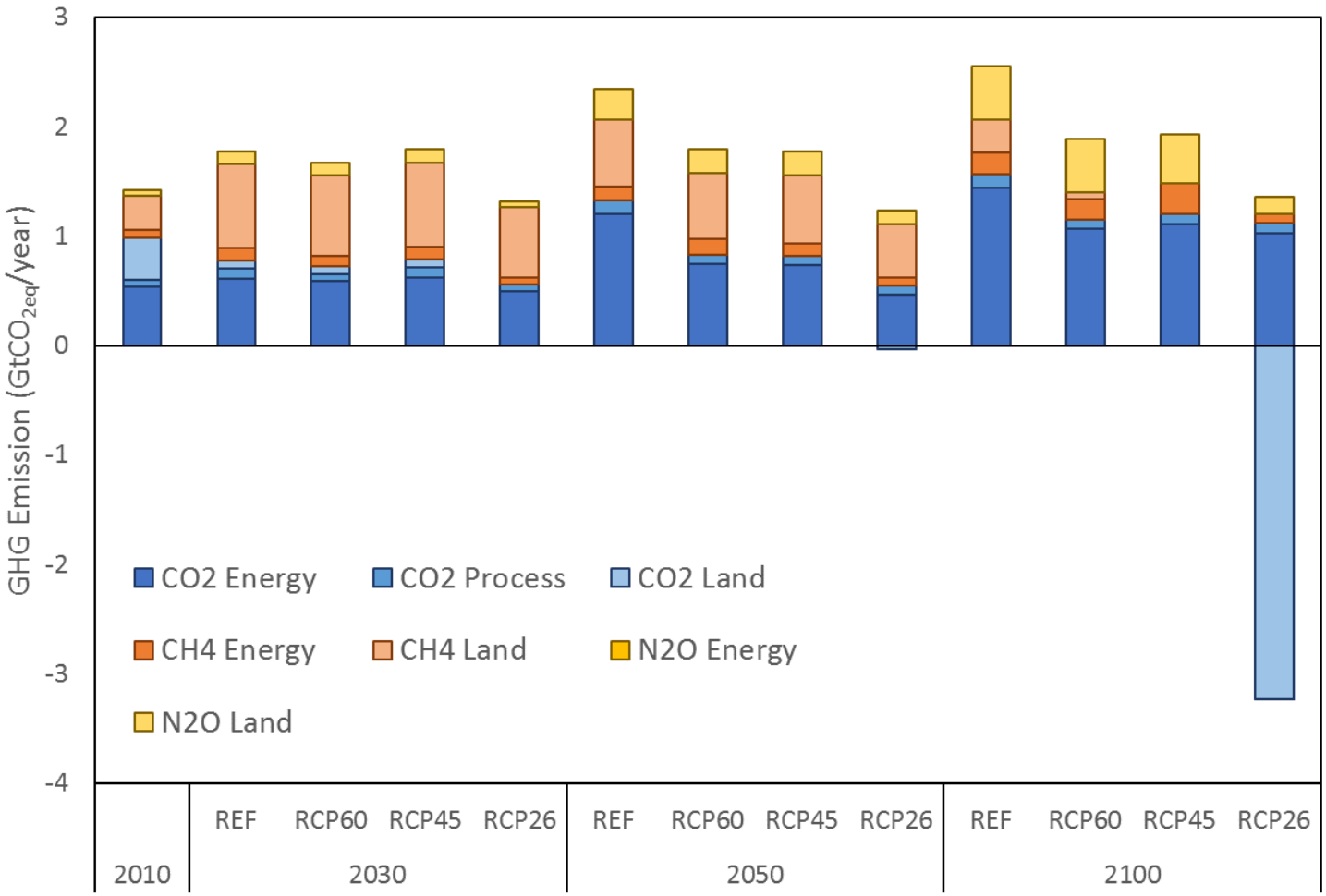


Figure 7-58 – Result summary of GHG emissions for Brazil ($MtCO_{2eq}$)

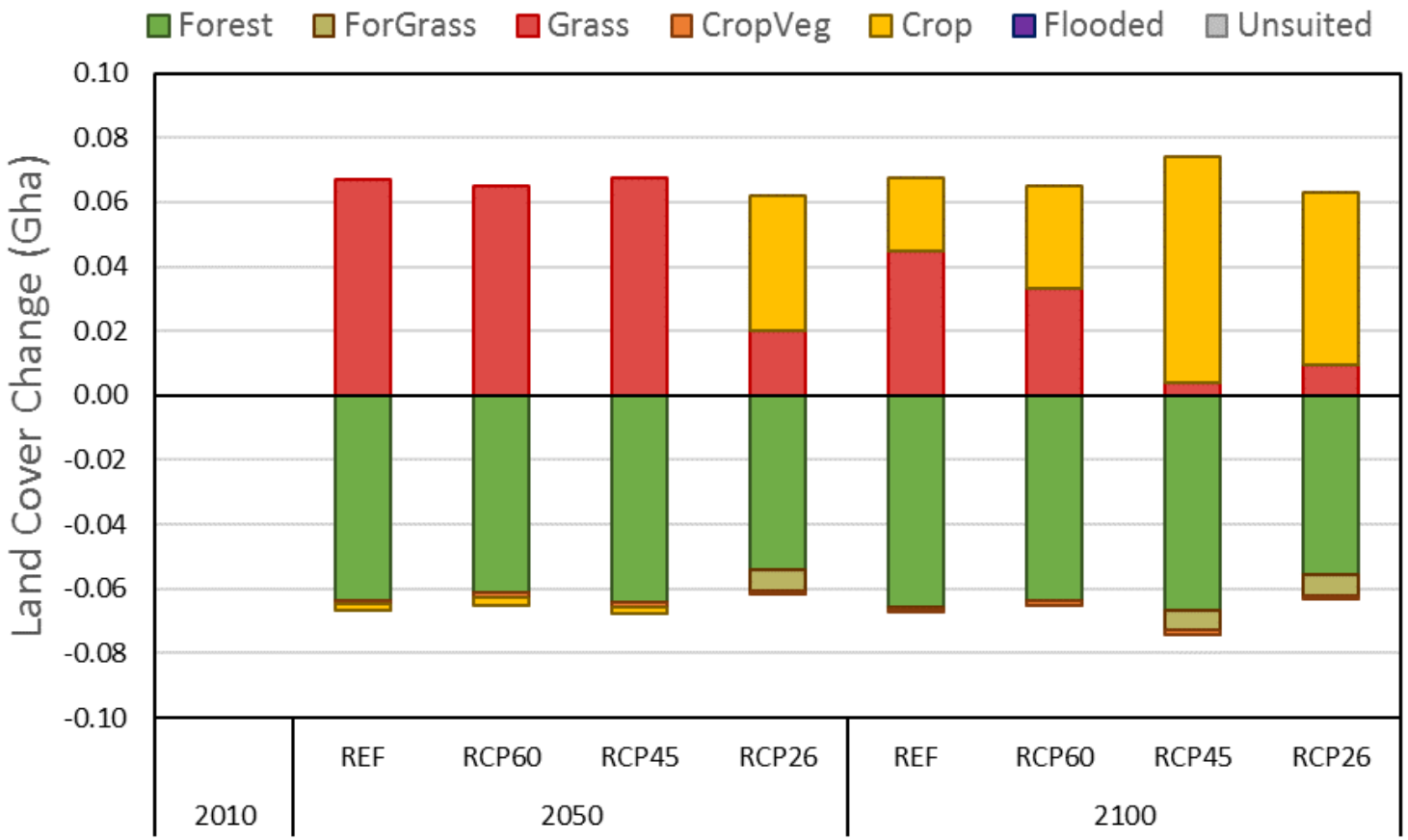


Figure 7-59 – Summary of land cover changes for Brazil (Gha)

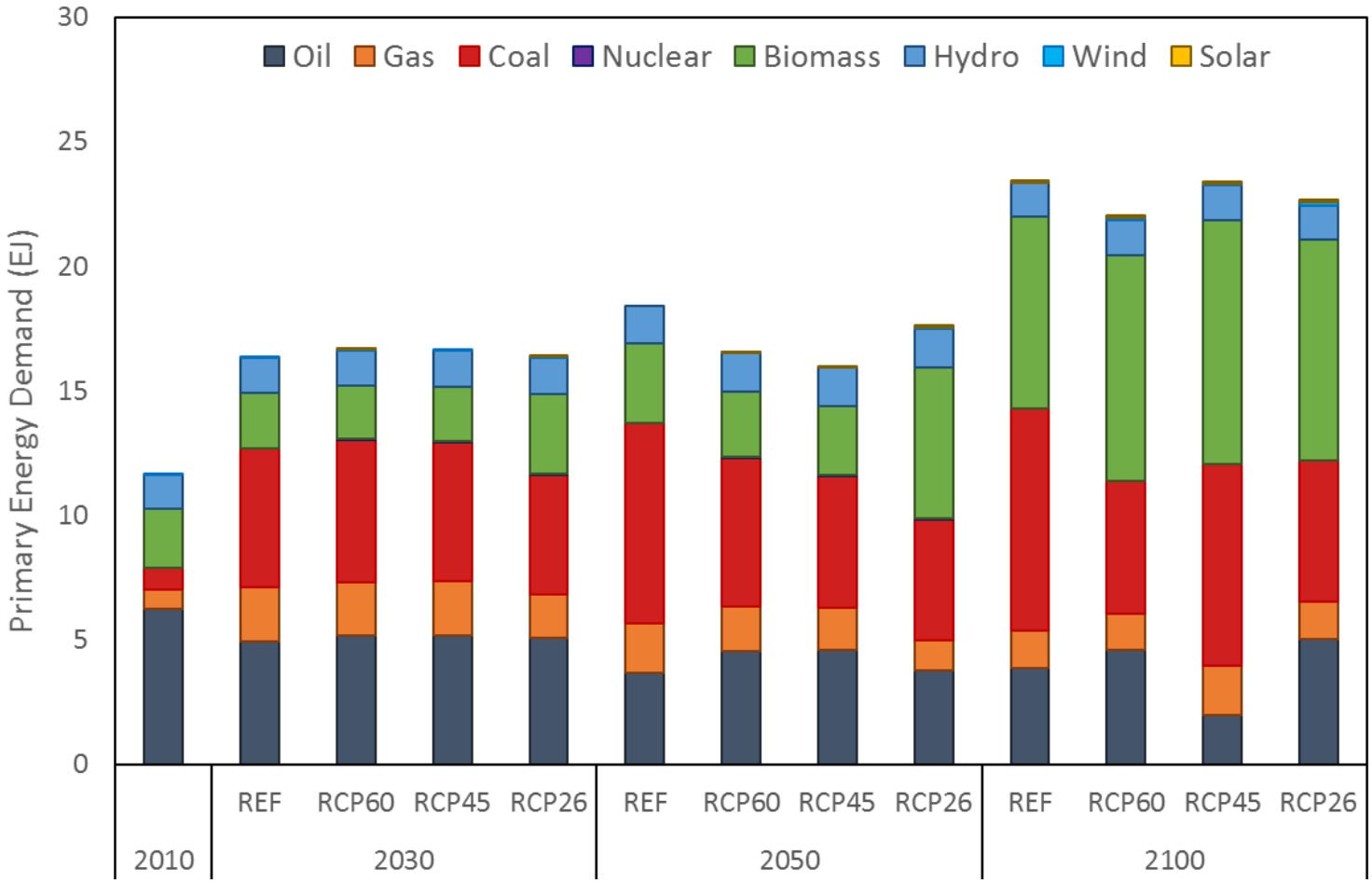


Figure 7-60 – Summary of primary energy demand for Brazil (EJ)

Despite the relatively similar profiles for primary energy demand, there are still conditions that could lead to a decrease in GHG emissions, for instance, by applying CCS to fossil fuels and bioenergy. Figure 7-61 presents the summary for CCS deployment in Brazil, which favours BioCCS instead of Fossil CCS.

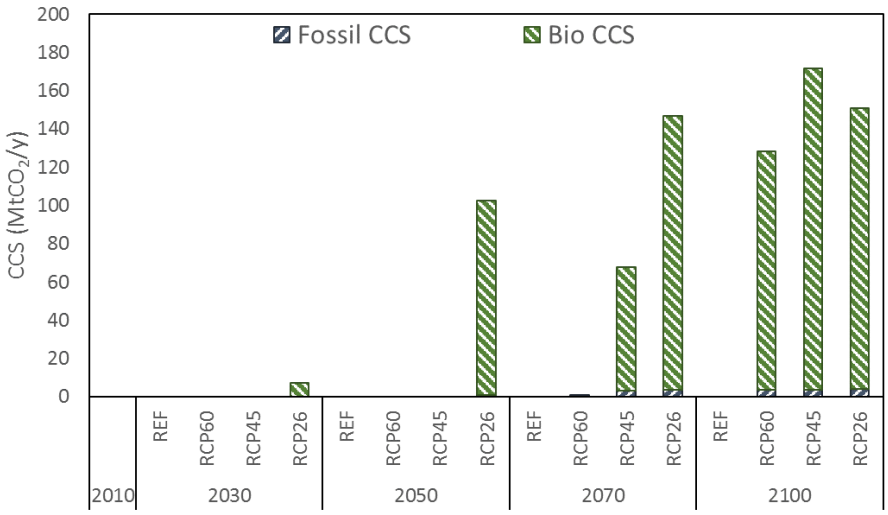


Figure 7-61 - Summary of CCS for Brazil ($MtCO_2$)

BioCCS is applied mainly to liquid biofuels, such as ethanol. Additionally, the use of CCS in the production of synthetic fuels from biomass gasification is also relevant for achieving high levels of captured CO_2.

Thus, the result show that Brazil could take significant advantage of CCS associated to bioenergy in order to reduce its GHG emissions. However, there are significant barriers for the development of the necessary conditions for enabling large scale CCS projects. Most importantly, in order to enable CCS as a mitigation option, proper regulatory framework must be enforced as well as specific policies towards public awareness and acceptance, as discussed in COSTA (2014).

Finally, the overall effect of the different RCPs for the Brazilian energy and land system are presented in Figure 7-62, which presents the total long-term GHG emissions for each scenario. Also, the target established at the Brazilian INDC (BRAZIL, 2015) is presented. This allows to properly evaluate how the Brazilian intended objective contributes towards achieving an increase of mean surface temperature under a 2°C scenario.

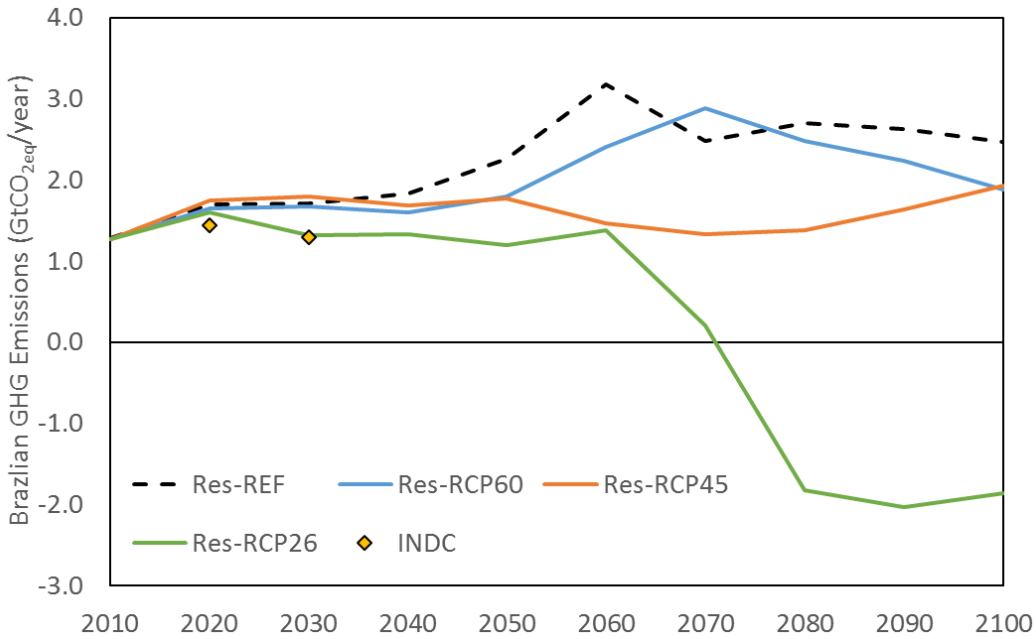


Figure 7-62 – GHG emissions for Brazil in the scenario protocol and the INDC

Source: INDC from BRAZIL (2015)

As it can be seen in Figure 7-62, the Brazilian INDC is within the range of the optimum profile of the RCP 2.6 for Brazil. This would suggest that the Brazilian INDC is very likely to be in good agreement with the necessary efforts to maintaining the increase in the global mean temperature under 2°C.

Nonetheless, the INDC of each country presented at the Paris Conference (COP21) only sets target to 2025 or, at best, 2030. However, the findings of this study strongly suggest that the true challenges towards achieving stringent climate targets are still to come, more specifically starting after 2030.

The results for Brazil suggests that all scenarios have a narrow range of GHG emissions up until 2050. Thus, the first challenge Brazil has to face is to simultaneously keep GHG emissions relatively constant until 2050 and still allow for economic growth and social development.

However, since all scenarios analysed in this study suggest such a narrow range of GHG emissions until 2050, this can hardly be defined as a major challenge, especially when compared to the additional efforts needed to diverge from less stringent scenarios beyond 2050.

In fact, up until 2015, the Brazilian economy has deviated from the SSP2 pathway of development due to recent economic crisis. This would suggest that achieving the INDC goals are relatively easier than ever, which means that even at a reference scenario

Brazil can achieve its goals. However, in order to return to a path of economic growth, this achievement, and the policy and investment decisions involved, can lead to a lock-in, which in turn will backfire towards creating additionally more stringent goals.

For instance, Res-RCP45 suggest that, for contributing to keep global warming under 1.8°C (mean value relative to 1986–2005), the Brazilian GHG emissions should remain under 2.0 $GtCO_{2eq}$. Again, this can be an enormous challenge to be achieved whilst still allowing for consistent economic growth and development.

On the other hand, when contributing for RCP 2.6 and a global warming of under 1.0 °C (mean value relative to 1986–2005), the Brazilian emissions need to plunge rapidly, achieving negative values of about 2.0 $GtCO_{2eq}$. This would suggest a rapid reduction of about 4.0 $GtCO_{2eq}$ in under 20 years. Not only that, but emissions continue to remain approximately at the same value until 2100.

Hence, despite the apparent good agreement of the Brazilian INDC towards keeping the increase of mean surface temperature under 2ºC, the findings of this study suggest that the true challenges are still to come. Brazil will need to face the need to keep the GHG emissions in check, whilst still allowing for economic growth and social development.

7.7.2. Regional Results

In this section, the results of each of the 18 regions detailed by the global model will be briefly discussed, focusing on the regional contribution to total GHG emissions. The summary of GHG emissions per region at selected years are presented in Figure 7-63 for all scenarios.

Individually, each of the 18 regions could be addressed in great detail, as performed for Brazil in the previous section. However, general implications of the RCPs can be interpreted by the data presented in Figure 7-63.

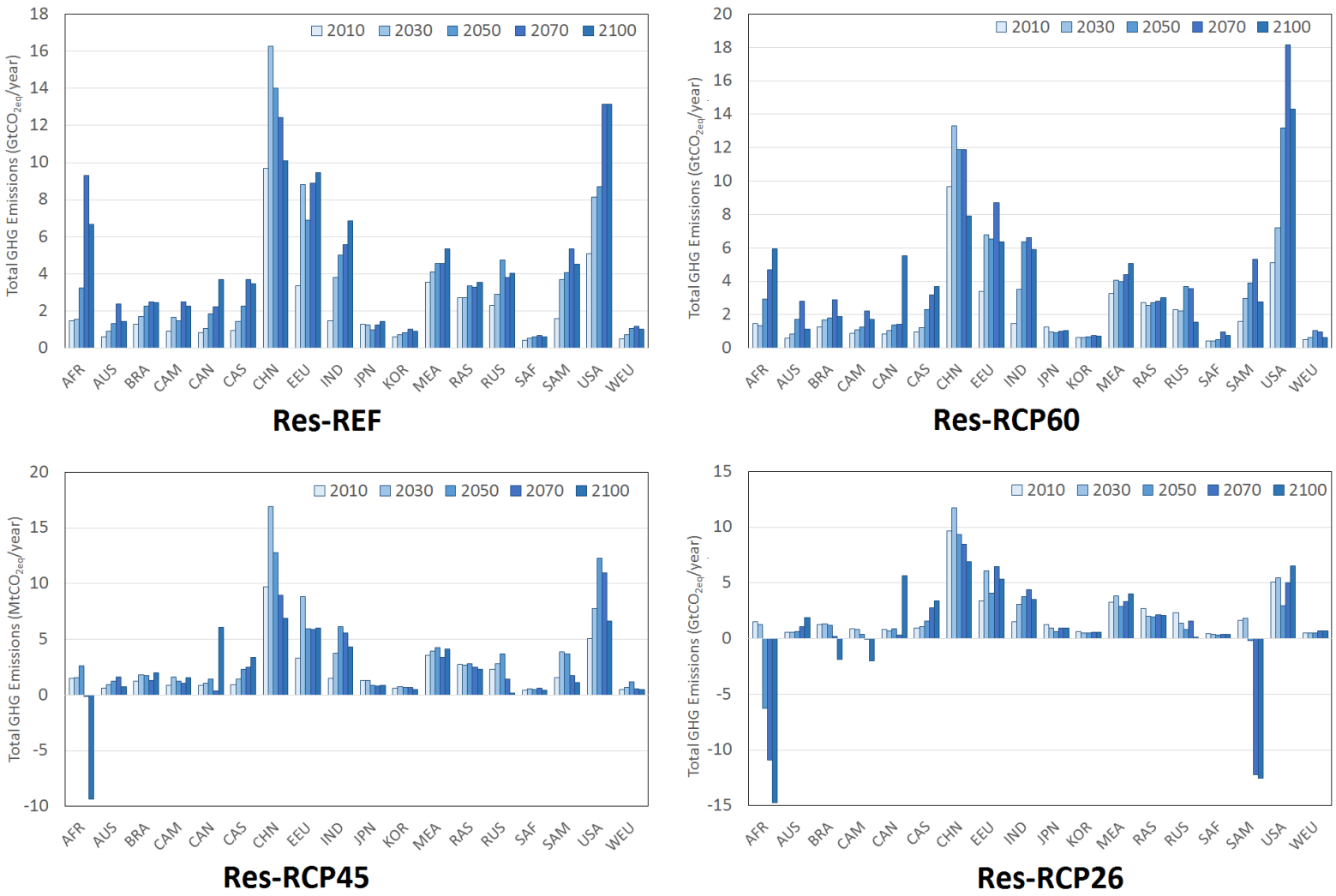


Figure 7-63 – Regional GHG emissions for all scenarios ($GtCO_{2eq}$)

In Res-REF, most of the regions continue to increase their emissions from 2010 to 2100. There are a few exceptions, such as Africa (AFR and SAF), China (CHN) and Europe (EEU and WEU), that present a peak of emissions before 2100. Nonetheless, the most interesting results come from the RCP scenarios.

Res-RCP60 presents a global reduction in GHG emissions, but there are regions which do not follow this pattern. For instance, Canada (CAN) and United States (USA) present higher emissions on the second half of the century at the Res-RCP60 than at the Res-REF. In both cases, this behaviour was caused by an increase in energy-related CO_2 emissions.

Even though it seems contradictory to increase energy emissions at a carbon constrained scenario, this was made possible by additional mitigation in other regions, such as Africa (AFR), Latin America (BRA, CAM and SAM) and even Europe (EEU and WEU). Overall, most of the reductions in emissions come from the land system, particularly from land cover change.

As a more stringent scenario, Res-RCP45 provides very different results. Whilst instantaneous peaks of emissions relatively higher than Res-REF can still be observed, both the emission at the end of the century and the cumulative emissions for all regions are smaller than in Res-REF and Res-RCP60.

It is worth noting that Africa (AFR) is able to contribute with net negative emissions starting from the second half of the century. In fact, in 2100 the African region reduces emissions, relative to the base year, at almost negative 640%. This is an impressive amount of mitigation being achieved primarily from the land system, which greatly contributes to fulfilling the RCP 4.5 target emissions.

This is the first scenario in which net negative emissions from the land system are apparent from all regions. However, it is worth noting that the role of the land system in achieving net negative emissions is widely controversial and attributed to large uncertainties (FEARNSIDE, 2000; IPCC, 2003; DAIOGLOU, 2016).

At this point (and even more so on the more stringent scenarios), the model uses the land system as a carbon sink, primarily due to reforestation and afforestation. There still a lot of uncertainties to the true global mitigation potential, since the changes in carbon stock are related to the relative changes in soil properties, land use, environmental conditions, weather and flora. Additional issues that are hard to represent in a global model are property ownership and land access policies, which can also have significant effect on the development of the land system.

Thus, a global model usually simplifies the process with general and average values which can, in turn, be either overestimated or underestimated. For this reason, regional models with higher details (such as using higher spatial resolution) are extremely important tools for assessing this issue in a more consistent way.

The other reason why using the land system as a carbon sink can be controversial is that the mitigation achieved is only relevant for the moment it was applied.

For instance, assume that, at a given year, the land system contributed to compensate for higher emissions, either from the energy system or even positive emissions from the land system itself. In the next years, if the land system is not used again, the other emission sources could easily exceed the carbon target. Or even additional efforts will be needed in order to reduce the positive emission sources.

In this context, another critical issue is that the mitigation potential is directly related to cumulative land use changes. Since there are croplands and grasslands that must be used for food and energy production, land cannot be converted into land uses with higher carbon stock indefinitely.

Ergo, the land system can be viewed as an easier road towards achieving the climate target, such as the RCP. But in all likelihood, early exhaustion of this mitigation option will only postpone, and most likely hinder[15], the necessary changes needed to actually reduce emissions form the energy system[16].

Nonetheless, the land system is extremely important for achieving even more stringent climate targets, such as those implied by RCP 2.6. The results show that Africa (AFR) and Latin America (BRA, CAM and SAM) are responsible for a considerable portion of the mitigation achieved in the Res-RCP26, most of which is achieved by the land system.

Meanwhile, regions such as China (CHN), United States (USA), Europe (EEU and WEU), and at smaller scale even India (IND) and Middle East (MEA), are able to continue exhibiting relatively high emission profiles, even though they do reduce their overall GHG emissions. Under the context of international negotiations for a climate agreement, there are significant ethical and geopolitical controversies in allowing this sort of situation to occur.

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[15] Possibly allowing the extension of a carbon lock-in.

[16] Including emissions from industrial processes, waste and fugitive sources.

Total emissions are not the only parameters used to compare regional emissions. Since each region is attributed a specific population and economic growth in the SSP2 scenario, it is suitable to compare emissions in regards to these parameters. Thus, two carbon intensities were calculated: related to population (in tCO_{2eq}/habitant); and related to GDP (tCO_{2eq}/kUS$). Results for selected regions are presented in Figure 7-64 and Figure 7-65, respectively[17].

The selected regions were composed by two representatives of developed countries (EEU and USA), the BRICS countries (BRA, CHN, IND, RUS, SAF) and a region representative of lower income countries (AFR).

As can be seen in Figure 7-64, regions such as Europe (EEU), India (IND) and China (CHN) present consistently carbon intensities higher than those in the base year for all scenarios. Brazil (BRA) and United States (USA) also have similar profiles, presenting a reduction on the carbon intensity only at the Res-RCP26. Meanwhile, Russia (RUS), South Africa (SAF) and Africa (AFR) present a wider variation, with highly reactive intensities depending on the scenario.

In regards to the carbon-to-GDP intensity, the basic profile is the same for all regions, where the index decreases exponentially until the end of the century. An exception happens for both developed regions (EEU and USA), where the intensity actually increased from 2010 to 2020 and only then decreased at roughly the same rate. Russia (RUS) presents the most erratic behaviour of all the sampled regions.

[17] Additional results can be found in Annex 2.

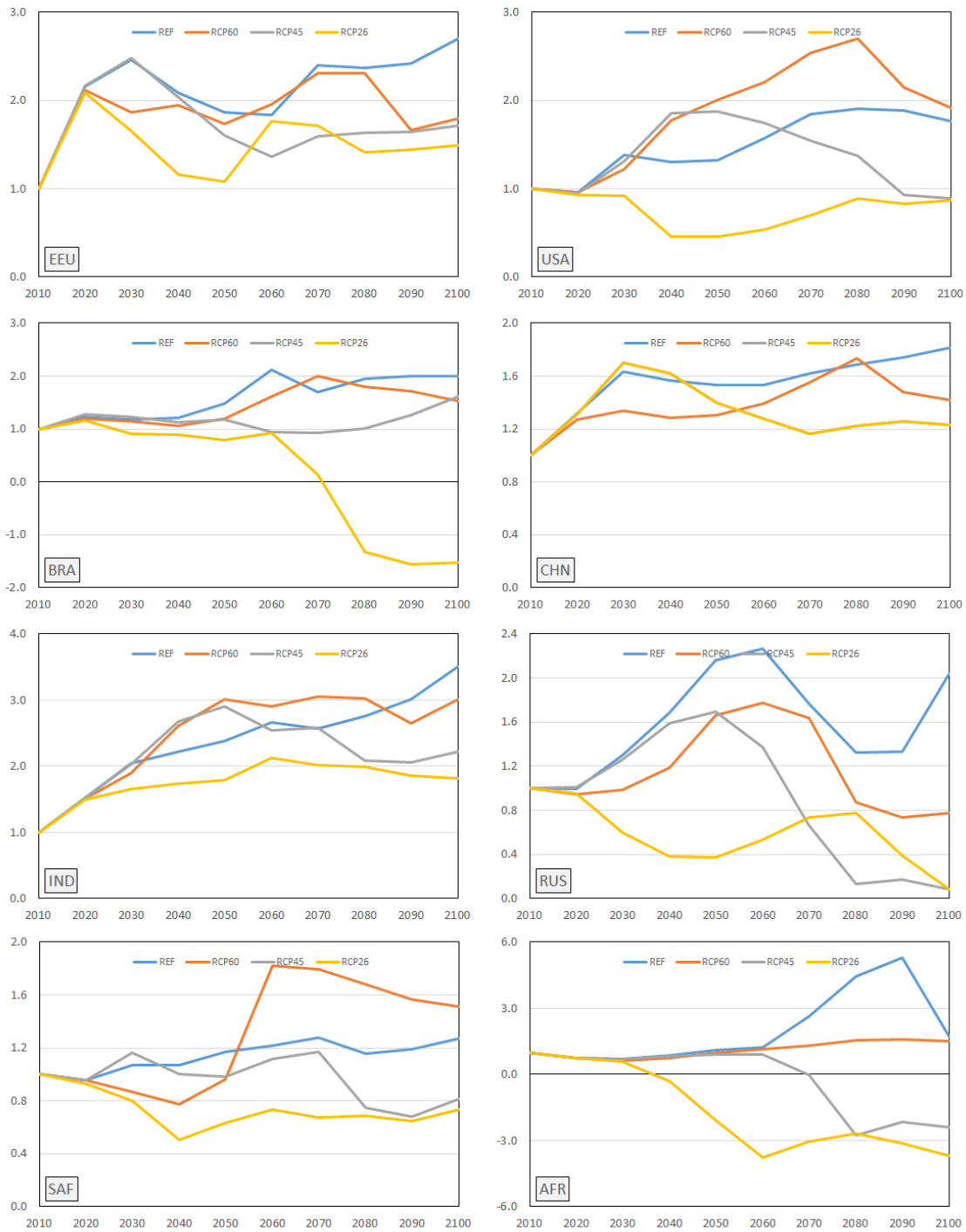


Figure 7-64 – Relative carbon emission per population for selected regions (2010 = 1.0)

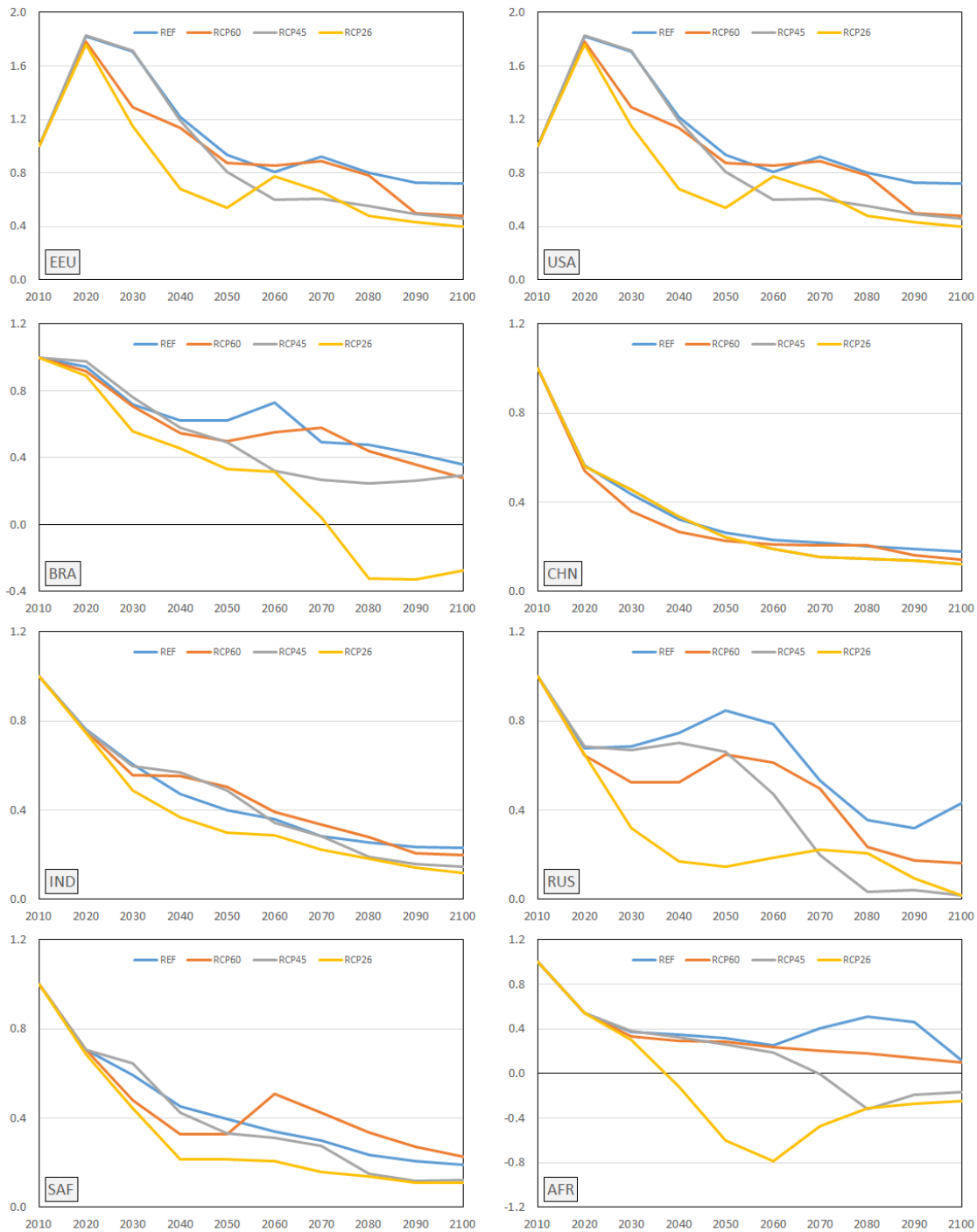
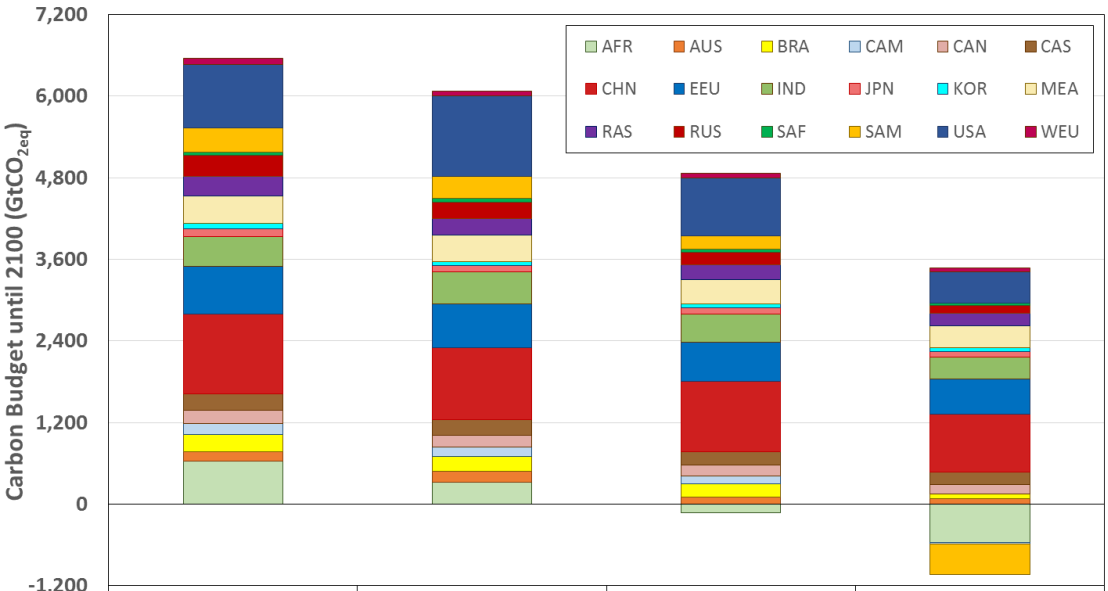


Figure 7-65 – Relative carbon emissions per GDP for selected regions (2010 = 1.0)

Finally, the results of the model provided suggestion as to the optimum design of carbon emission for all regions in order to reach each RCP scenario. As such, each region provided very different roles in the achieving of the global goal. This can be measured by the carbon budget attributed to every region at each scenario.

The carbon budget of every region, and for all four scenarios, is presented in Figure 7-66. The carbon budget is the total amount of cumulative GHG emissions allowed

by the model, from 2010 to 2100, at optimum solution, to each region in order to achieve the emission profile defined by each RCP.



	Res-REF	Res-RCP60	Res-RCP45	Res-RCP26
WEU	84	71	63	57
USA	932	1188	856	456
SAM	356	320	195	-449
SAF	52	61	44	33
RUS	312	236	185	118
RAS	278	240	224	187
MEA	412	391	354	324
KOR	78	64	59	51
JPN	108	95	89	83
IND	439	466	410	328
EEU	710	651	575	508
CHN	1170	1049	1035	855
CAS	236	228	203	189
CAN	195	177	161	133
CAM	170	138	113	-20
BRA	250	225	191	65
AUS	140	157	105	83
AFR	629	319	-124	-569

Figure 7-66 -Carbon budgets for every region in every scenario (period: 2010-2100)

As can be seen in this figure, there are regions with highly positive budgets (such as China, Eastern Europe and United States), regions with relatively modest budgets, and even regions with net negative budgets (Africa and Central America and South America). Despite presenting net negative emissions at the end of century in Res-RCP26, Brazil still presents a net positive carbon budget.

In a simplistic approach, these carbon budgets can be seen as shares of the total GHG emissions which can be attributed to each region at a global climate agreement.

However, this approach does not simply disregard socioeconomics impacts of imposing a carbon budget completely, but also is highly controversial from an ethical perspective.

It is worth mentioning that, because this is a linear programming model of perfect competition and perfect foresight, the results, although optimized, can be socially and ethically undesirable. As such, as previously mentioned, integrating the results from the model developed in this study to a macroeconomic model, such as a CGE, could not only help balance the socioeconomic impacts, but also provide a stronger consistency of the results of this study with the macroeconomic scenario.

8. Final Remarks

This final chapter addresses the final remarks of this study. This includes summarizing the motivation of this study, the methodological procedure used and the main findings. Also in this chapter, the limitations of this study are discussed, with additional suggestions on future studies to continue and improve the model developed in this thesis.

8.1. Findings, contributions and policy implications

An integrated long-term optimization model was developed for the global energy and land systems. This is the first step into the development of an Integrated Assessment Model, which is widely used by the climate change scientific community to assess long-term scenarios. This type of model is nearly unprecedented in terms of non-OECD countries and is currently being developed in Brazil (in this study), India and China.

Still, it is important to note that the development of a global modelling tool from a Brazilian perspective will help the scientific community, especially national research institutions, which are undergoing climate change studies. Additionally, the assessment framework developed in this study could also be usefull towards supporting policy design.

The assessment of global climate targets could provide relevant information to experts and decision-makers on the possible development strategies and repercussions of long term climate scenarios.

Even though the Paris Agreement was a meaningful global achievement towards achieving a global consensus and cooperative action in tackling climate change, it is not the end of journey. There is still need for ongoing efforts, both in the scientific community and the geopolitical scene. It cannot be seen as a fulfilled objective, but a call for further action.

This study reinforces this message, suggesting that the pathway towards achieving stringent climate targets will be more challenging after 2030. As such, even if all national pledges in the Paris Agreement are fulfilled, the future efforts will need to be increasingly higher and, therefore, associated with a higher level of difficulty for general acceptance from all involved parties.

ROGELJ *et al*. (2016) state that the action by virtually all countries improves prospects for further collective action, which must be the fundamental basis of any adequate response to climate change. Charting development pathways that can hold warming to well below 2 °C will thus require a renewed effort of the social and physical science communities alike.

In this context, the assessment framework developed in this study could help Brazil strengthen its position and become even more active in the climate negotiations, for it will be supported by assessments in accordance to international literature on the impacts of socioeconomic background and its environmental impact.

Another interesting possibility is using the global integrated energy and land system model here developed as a provider of the boundary conditions for a more detailed regional or national model, such as MESSAGE-Brazil.

Hence, the global model could provide useful data for calibrating the national model, such as international energy and carbon prices, availability of imported energy resources and foreign demand for energy products. This level of consistency is a current major limitation of regional and national models, which create assumptions on the foreign energy market.

For instance, in a reference scenario the foreign demand for crude oil and oil products would be relatively higher, and therefore more economically favourable, than in a carbon constrained scenario.

However, a global pursuit for a climate agreement could create new markets and energy demands, such as for bioenergy products. Ergo, even though the oil industry could be affected, the Brazilian economy could still profit from the increased foreign demand for biofuels, such as ethanol, and still take advantage of mitigation options, such as BioCCS.

Thus, the methodological tool here developed could provide the basis for the development of a set of dynamic policies in the sub-national, national and global levels. These policies include not only energy and environmental policies, but also strategies for the development of both existing and new markets, labour and even targeting regional development.

Therefore, the coupling of a global energy and land systems model with a high detailed national one is favourable toward the assessment of the Brazilian energy and land systems, the opportunities for the economy and simultaneously the role Brazil could have in a long-term global climate agreement.

The findings of this study suggest that the Brazilian INDC is very likely to be in good agreement with the general objective of the UNFCCC Paris Agreement. On the other hand, when contributing for very strict climate scenarios, Brazilian emissions need to plunge rapidly, achieving negative values before the end of the century.

Hence, despite the apparent good agreement of the Brazilian INDC towards the goals of the UNFCCC, the findings of this study suggest that the true challenges are still to come. Not only that, but Brazil will need to face the need to keep its GHG emissions in check, whilst still allowing for economic growth and social development.

The scenario protocol here developed was based on combining an interpretation of the Shared Socioeconomic Pathways 2 (SSP2) scenario with the Representative Concentration Pathways (RCP). A reference scenario was also considered.

The findings suggest that the SSP2 is consistent in achieving the RCP scenarios. This means that the model was able to find an optimum solution whilst constrained for the emissions profile of the RCP. Besides, the Reference scenario's GHG emissions profile is consistently lower than that of RCP 8.5.

This suggests that the Reference SSP2 scenario, which presented a global carbon budget of around 6.7 $TtCO_{2eq}$, between 2010 and 2100, is inconsistent with the emission profile of the RCP 8.5, which has a carbon budget of about 9.5 $TtCO_{2eq}$. An equally important result is that the SSP2 is consistent with the more restrictive scenario assessed in this study, the RCP 2.6, with a carbon budget of 2.0 $TtCO_{2eq}$.

This was made possible by the combining efforts of all 18 regions of the model, most importantly the Africa region and the regions that compose Latin America (Brazil, South America and Central America). These regions depended highly on land use change mitigation as well as BioCCS in order to present net negative emissions by 2100 at the most stringent scenarios.

The mitigation from the land system was comprehensively important in achieving the relatively lower emission profiles of the different RCPs. However, the achievement of net negative GHG emissions from the land system is widely controversial and attributed to large uncertainties.

Global models usually simplify the land cover change processes with average values, which can create large uncertainties to the mitigation and cost potential of this mitigation option.

The other reason why using the land system as a carbon sink can be controversial is that the mitigation achieved is limited, due to limited availability of land suitable for land cover change.

Additionally, the mitigation happens only once, when the land cover change occurs, without promoting any cumulative changes to the production system and economy. Therefore, the early exhaustion of this mitigation option will only postpone, and most likely hinder, the necessary changes needed to actually reduce emissions form the energy system.

On the other hand, results also show that Latin America (especially Brazil) could take significant advantage of CCS associated with bioenergy in order to reduce its GHG emissions. The fragility and necessary conditions for enabling this mitigation option are discussed in the following sections.

8.2. Current limitations and suggestions for future studies

The results of this study are in good agreement with the most recent scientific literature. However, there is still need for caution when analysing the detailed results and findings of this study. The reason is that this study is the first of a series of scientific assessments that must be developed in order to continue to improve an integrated assessment model.

As in any mathematical model, there are intrinsic limitations that must be taken into account when assessing results. Thus, this section addresses the main limitations of the methodological procedure used in this study. Another relevant source of limitations to the assessment performed in this study lies on the limitation of available data (and the consistency of databases), especially at the level of details needed to perform this study.

Thus, in the next sub-sections, the main limitations of this study are presented. For each, suggestion of future studies and methodological procedures are also being presented in order to overcome these drawbacks and contribute to the development of a model with a higher level of coverage, consistency and detailing.

8.2.1. Overall

This section explores the overall limitations of the model developed in this study and, therefore, of the results presented.

First of all, it is important to state that the model developed in this study is the first step into the development of a larger modelling framework. As such, it is still quite limited as an Integrated Assessment Model, especially when compared to other IAMs found in the literature, where other interactions and systems, not present in our model, are also considered.

First of all, it is worth emphasizing the need for adding the effect of the socioeconomic feedbacks and drivers into the energy and land systems. More specifically, by allowing the flow of information between a macroeconomic model and the optimization model, a higher level of consistency can be achieved.

Thus, the development of an economic framework is needed to study the development of the economy and production factors under a level of regional and sectorial representation that is compatible with the model presented in this study. The most commonly considered tool for addressing this issue is a Computable General Equilibrium Model.

Not only CGE models can provide the detailed and consistent data for economic development, they can also be used to estimate the demand of energy services and the development of the energy sector (including, for instance, the oil and gas industry).

Thus, macroeconomic scenarios could be developed and detailed. This is especially relevant for developing interpretations of the SSP scenarios, which only provide general guidelines of socioeconomic development and very few quantitative data. Hence, a CGE model could provide quantitative interpretations of the SSP scenario and, in turn, be used to calibrate results from the energy and land models.

In the context of IAM, it is also interesting to directly address the relationship between GHG emissions and the climate system. As such, a direct approach is to use the emission profile provided by an IAM to assess the effects on the long-term climate conditions at a global climate model. Another interesting approach is to use the climate model to set a global climate target and use the resulting emission profile (or carbon budget) as an input into the IAM model. This approach is similar to the one used in this study for the RCPs.

One of the tools widely used in IAMs is the Model for the Assessment of Greenhouse-gas Induced Climate Change, or MAGICC. This tool has been used to estimate the climate system impacts of GHG emission trajectories. MAGICC is a reduced complexity coupled global climate-carbon cycle model, in the form of a user-friendly software package that runs on a personal computer (MCCOLLUM *et al.*, 2011). Several IAM models in the literature, such as AIM, MAGPIE-REMIND and MESSAGE-GLOBIOM, are currently coupled to MAGICC (IIASA, 2015).

Therefore, the coupling of the model developed in this study and a climate model, such as MAGICC, could create the opportunity for further studies and assessments of higher complexity. Also, this methodology would enable independent analysis of climate scenarios, i.e., independent of data from literature or scientific cooperation. However, in order to enable this coupling, there is need of assessing the emission and mitigation options of additional GHG, currently not included in this study.

Another proposal for future studies is to incorporate the effects of climate change adaptation into IAMs. However, this would involve highly complex parametrizations and interactions with climate models with intrinsically higher complexity than MAGICC.

Nonetheless, only through this methodology the complex relationship between adaptation, impacts and mitigation could be assessed in a systemic and consistent way. For instance, the results of a typical IAM for a Reference scenario have very limited influence of mitigation actions, but completely disregards the effects of climate change in the energy and land systems.

Even though this is a typical approach in the scientific literature, by disregarding the effects of adaptation and impacts of climate change in a Reference scenario the results are not only inconsistent, but most likely underestimate the costs of a Reference scenario. It must be noted that this suggestion is highly complex and is still being developed by the IAM teams around the world.

The following sections addresses the limitation in the land and energy systems, individually and in greater detail.

8.2.2. Land System

The optimization model developed in this study included not only the energy system, but also the land system. This is the first known successful attempt to use

MESSAGE to assess the land system, especially in a simultaneously approach with the energy system.

It must be noted that adapting the optimization tool, originally developed for the energy system, to incorporate the dynamics and complexity of the land system took considerable effort. Indeed, significant effort went into creating, analysing and compiling the necessary data for developing the land model.

Despite all this, there are several limitations of the methodology used in this study to address the land system.

Primarily, the complexity of the land system was dramatically simplified. In highly detailed land models, the relationships between several aspects are simultaneously incorporated, such as: geological formations, climate and weather conditions, crop yields, carbon stock and economic feasibility.

As such, this study could benefit from improvements in the analysis of data on crop yields, detailed assessment of carbon stocks (above and below ground) and emission profile of crops and livestock.

A common approach of land use models for tackling this issue is using extremely highly detailed data in a spatially explicit format. This sort of model considerably increases the complexity of the model and solution methods applied. Data availability and increase complexity are typical limiting factors into the development of spatially explicit models.

The development of land model must also take into account the high levels of uncertainties in data and estimates from the literature. The approach of this study was to use mean values for different land covers and regions, which only increases the uncertainty of the behaviour of the land model.

Another major issue in the land model developed in this study is the need for adjusting the cost of production of crops and livestock. This is an example of how a CGE model can contribute to the calibration of the model, since the production costs are related to the costs of production factors, such as land, labour and capital.

The economic calibration is also an important aspect to the dynamics of the land system and the competitiveness of the agriculture sector of each region. Additionally, it also affects the mitigation cost of land-based options, such as bioenergy crops and land cover change.

There are also mitigation options not considered in this study, not only from the agriculture sector but also related to land cover changes and land protection policies. For

instance, it is possible to mention more detailed assessments of mitigation options in fertilizer use, production methods, managed forests and recuperation of degraded grasslands.

Finally, it is worth including the assessment of land protection policies and ongoing land-based policies in all regions used in this model. In fact, the SSP scenarios also differentiate themselves in the land policies and strategies; for instance, policies for protection of biodiversity and indigenous tribes and policies for regulating the payment of environmental services. Another example is the development of policies that compensate the mitigation provided by reforestation and afforestation, such as those proposed by the main results of this study for regions such as Africa and Latin America.

8.2.3. Energy System

This section explores the limitations of the energy system of this study. The most basic limitation of this study lies on the data used and processed. There is need of additional efforts to enhance the energy resources and energy technologies representation within the model.

The oil resource estimates performed in this study were highly detailed and in accordance with the most recent and relevant available literature. However, there are still available improvements which could be made in order to enhance the model representation and performance.

An example of improvements in the oil representation is the inclusion of a set of oil types, for instance differentiating by range of density (°API) and sulphur content. Consequently, there would be need of differentiation the refineries by input.

An advantage of increasing the oil categories is to have a better representation of the global oil industry, especially relating to the competitiveness and accessibility of different oil grades in the global market. Another aspect that is directly related is the difference of yields to different oil products, which also could affect the decision of the model.

There are considerable limitations to the resource data used in this model, especially for a few of the oil and gas categories used in this study. On example is the limited approach towards estimating the potential for Enhanced Oil Recovery (EOR).

However, additional data and methodologies would have to be used to enhance the assessment performed in this study.

Another example is related to shale gas resources, most importantly the estimates for natural gas liquids. There are very few available data for this information outside the US, which greatly hindered the assessment of this study. Additionally, there are other unconventional gas resources not considered in this study, such as hydrates, that could be incorporated into the model.

Another proposed assessment to improve the model representation of the global energy system is to improve the cost data of energy technologies across regions. By incorporating aspects such as location factors, learning rates and spatial diffusion, the cost dynamic of energy technologies could be considerably improved.

Indirectly related to this issue is the availability and acceptability of a set of controversial technologies, such as CCS and nuclear energy. Both these technologies are examples of getaways that the model frequently used to reduce GHG emissions in the energy system. However, their application is not only conditional to public acceptance, but also to the need of proper regulatory frameworks.

Carbon capture and storage was widely deployed in all RCP scenarios in this study. Therefore, the availability of CCS considerably changes the mitigation cost curve of the energy system and, therefore, the potential mitigation achieved in the scenarios.

Therefore, scenarios with constraints in the penetration or availability of CCS could lead to very different results. Additionally, there is a possibility that, in scenarios without CCS (more importantly BioCCS), the model would find unfeasible to comply with the more stringent carbon budgets. However, to confirm this hypothesis new scenarios should be evaluated in future studies.

If confirmed, this would emphasize the need for the development of a policy framework for enabling carbon capture and storage. Even then, there is still need for policies for the internalization of the externalities of GHG emissions, such as carbon taxes or a carbon cap-and-trade system.

In this context, an interesting proposal for additional studies is the assessment of conditions for phasing-out fossil fuels from the energy system, most importantly oil. The results of this study showed that even at the most restrictive scenario, RCP 2.6, oil products still played a role in the energy system.

However, under more stringent conditions, oil could technically be completely phased-out. However, there are not only technological repercussions in order to enabling

this process, but also significant repercussions to the economic and geopolitical frameworks. This would not only directly affect regions and countries whose economies are highly oil-dependent, but also create a whole new set of conditions to the international market and trade.

In regards to the other limitations of the study, there are considerable improvements to be made in the energy end use representation. One aspect, already mentioned, is related to the need for consistency between the macroeconomic scenario and the performance (in terms of demand and technology availability) of end-use sectors.

However, an additional aspect to be improved is the technological representation of each of the end-use sectors considered in this study. For instance, there is need for a detailed assessment of mitigation options, including energy efficiency and process substitution, in all sectors of the economy.

This could not only help improving the representation of the different sectors within the model, but also the mitigation cost curve of the energy system. This could also be result in a larger decrease in the energy intensity of a sector or region, specially due to the industrial sector.

In order to properly assess this in a global context, socioeconomic and cultural aspects, as well as consumer behaviour, must be taken into account. As such, each region has a specific contribution to reduce GHG emissions of the energy system, which must be assessed in an individual manner.

As previously mentioned, the model developed in this study only accounts for emissions of the most important GHGs: carbon dioxide, methane and nitrous oxide. Therefore, the enhancement of emission profiles for unconsidered gases (both global and local pollutants) could create a new opportunity for environmental assessments and analysis of co-benefits in climate scenarios.

Additionally, there is need for improving the representation of energy policies within the model. This includes not only current and projected policies, but also additional policies that could be analysed in a scenario framework. Examples of policies are renewable portfolios, energy security, fuel specification (e.g.: low sulphur diesel), biofuel blending standards, efficiency standards and even technology development and research portfolios.

Finally, one aspect that could help the model in the representation of the global energy system is a more detailed analysis of the logistics for energy transfer between regions. This would include not only the assessment of the current limitation towards

energy transfer for liquids (oil products and LNG) and solids (coal and biomass), but also the potential constraints for energy trade, such as port capacity addition and energy security policies.

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10. Annex 1 – Economic data for energy technologies

This annex provides the economical data for the energy technologies, such as energy source, the technology used, the investment cost and operation and maintenece costs. It is worth noting that the costs provides in these tables are average values from the literature.

Table A 1 and Table A 2 presents the power technology data for all energy sources.

Table A 1 – Power technology economic data (part 1)

Energy Source	Technology	Categories	Additional Details	Investment Cost	O&M (% of Inv.)
Betuminous Coal	IGCC	-	w/o CCS	2374	4.9%
	USC	-	w/o CCS	1635	3.5%
	SC	-	w/o CCS	1536	3.6%
	SubC	-	w/o CCS	1449	3.7%
	IGCC	-	w/ CCS	3123	4.9%
	USC	-	w/ CCS	2715	3.5%
	SC	-	w/ CCS	2715	3.6%
	SubC	-	w/ CCS	2704	3.6%
Sub-betuminous	USC	-	w/o CCS	1727	3.5%
	SC	-	w/o CCS	1636	3.5%
	SubC	-	w/o CCS	1543	3.6%
	USC	-	w/ CCS	3001	3.5%
	SC	-	w/ CCS	3027	3.5%
	SubC	-	w/ CCS	3153	3.5%
Lignite	SC	-	w/o CCS	1760	3.3%
	SubC	-	w/o CCS	1669	3.6%
	SC	-	w/o CCS	3266	3.5%
	SubC	-	w/o CCS	3390	3.5%
Natural Gas	GT	-	w/o CCS	563	2.0%
	NGCC	-	w/o CCS	751	3.1%
	NGCC	-	w/ CCS	1338	3.4%
	SubC	-	w/o CCS	1111	3.7%
Biomass	SubC	-	w/o CCS	3500	3.2%
	SubC	-	w/ CCS	6495	6.3%
	IGCC	-	w/o CCS	4000	6.0%
	IGCC	-	w/ CCS	4746	7.9%
Fuel Oil	SubC	-	w/o CCS	1111	3.7%
	Engine	-	w/o CCS	903	3.7%
Diesel	SubC	-	w/o CCS	1111	3.7%
	Engine	-	w/o CCS	903	3.7%

Source: Adapted from IRENA (2014) and IECM (2016)

Table A 2 – Power technology economic data (part 2)

Energy Source	Technology	Categories	Additional Details	Investment Cost	O&M (% of Inv.)
Pet Coke	IGCC	-	w/o CCS	2374	4.9%
	SubC	-	w/o CCS	1449	3.7%
Hydro	Large	All Categories	-	1750	2.0%
	Small	All Categories	-	2400	2.0%
Wind Onshore	100 km	All Categories	-	1700	2.0%
	200 km	All Categories	-	2000	2.0%
	1500 km	All Categories	-	2500	2.0%
Wind Offshore	100 km	All Categories	shallow	5000	2.7%
	100 km	All Categories	transitional	5630	2.7%
	100 km	All Categories	deep	6775	2.7%
	200 km	All Categories	shallow	5380	2.6%
	200 km	All Categories	transitional	6049	2.6%
	200 km	All Categories	deep	7245	2.6%
	1500 km	All Categories	shallow	6650	2.3%
	1500 km	All Categories	transitional	7460	2.3%
	1500 km	All Categories	deep	8850	2.3%
Solar	PV	All Categories	-	2200	1.5%
	CSP	All Categories	0h storage	5000	1.1%
	CSP	All Categories	7h storage	6310	1.6%
	CSP	All Categories	12h storage	7250	1.6%
Nuclear	PWR	-	Fuel: UO2 3.50%	3900	1.5%
	BWR	-	Fuel: UO2 3.50%	3900	1.5%
	APWR	-	Fuel: UO2 4.50%	4800	1.5%
	GCR	-	Fuel: UO2 3.50%	4500	1.5%
	PHWR	-	Fuel: UO2 0.72%	4000	1.5%
	PHWR	-	Fuel: UO2 0.85%	4200	1.5%
	LWGR	-	Fuel: UO2 2.00%	4800	1.5%
	FBR	-	Fuel: UO2/MOX	5300	1.5%
	HTGR	-	Fuel: UO2 8.00%	4800	1.5%

Source: Adapted from IRENA (2014), IAEA (2015a) and IAEA (2015b)

The next table presents the synthetic fuels technologies, Coal to Liquids (CTL) and Biomass to Liquids (BTL).

Table A 3 – Synthetic fuel technologies economic data

Parameter	Unit	CTL	CTL CCS	BTL	BTL CCS
Input		Coal	Coal	Biomass	Biomass
Output		Diesel	Diesel	Diesel	Diesel
CCS		No	Yes	No	Yes
Efficiency	% (LHV)	41%	42%	38%	39%
Investment	$/kW	926	954	785	816
Fixed O&M	$/kW/y	18.5	19.1	15.7	16.3

Source: Adapted from MEERMAN *et al.*, 2013

Finally, Table A 4 presents the hydrogen production technologies including natural gas reforming, Coal to Hydrogen (CTH), Biomass to Hydrogen (BTH) and electrolysis.

Table A 4 – Hydrogen technologies economic data

Parameter	Unit	NG Ref.	NG Ref. CCS	CTH	CTH CCS	BTH	BTH CCS	Electrolysis
Input		Natural Gas	Natural Gas	Coal	Coal	Biomass	Biomass	Electricity
Output		Hydrogen	Hydrogen	Hydrogen	Hydrogen	Hydrogen	Hydrogen	Hydrogen
CCS		No	Yes	No	Yes	No	Yes	No
Efficiency	% (LHV)	74%	74%	59%	59%	83%	83%	67%
Investment	$/kW	545	622	2086	2255	2285	2465	605
Fixed O&M	$/kW/y	24.0	47.0	41.4	44.8	45.4	49.0	18.1

Source: Adapted from LINDSAY *et al.* (2009), INL, 2010, DAIOGLOU (2016)

11. Annex 2 – Additional result data

This annex presents additional detailed data of the main results of this study. Table A 5 presnts the regional breakdown of the global GHG emissions dor selected years. Results are in $GtCO_{2eq}$ per year.

From Table A 6 to Table A 13, the results for carbon intensity related to population and GDP for all scenarios are presented. Units are in tCO_{2eq} per capita and tCO_{2eq} per thousand dollars of GDP, respectively.

Table A 5 – Regional breakdown of GHG emission in select years ($GtCO_{2eq}$)

Region	2010	2030				2050				2070				2100			
		Res-REF	Res-RCP60	Res-RCP45	Res-RCP26	Res-REF	Res-RCP60	Res-RCP45	Res-RCP26	Res-REF	Res-RCP60	Res-RCP45	Res-RCP26	Res-REF	Res-RCP60	Res-RCP45	Res-RCP26
AFR	1.5	1.5	1.4	1.5	1.3	3.2	3.0	2.6	-6.3	9.3	4.7	-0.2	-10.9	6.7	6.0	-9.3	-14.7
AUS	0.6	0.9	0.8	0.9	0.6	1.3	1.7	1.3	0.7	2.4	2.8	1.6	1.1	1.4	1.1	0.7	1.9
BRA	1.3	1.7	1.7	1.8	1.3	2.3	1.8	1.8	1.2	2.5	2.9	1.3	0.2	2.5	1.9	2.0	-1.9
CAM	0.9	1.7	1.1	1.6	0.8	1.5	1.3	1.2	0.4	2.5	2.2	1.1	0.0	2.3	1.7	1.6	-2.0
CAN	0.8	1.1	1.1	1.1	0.7	1.8	1.4	1.5	0.9	2.2	1.4	0.4	0.3	3.7	5.6	6.1	5.6
CAS	0.9	1.4	1.2	1.4	1.1	2.3	2.3	2.3	1.5	3.7	3.2	2.5	2.8	3.5	3.7	3.4	3.4
CHN	9.7	16.3	13.3	16.9	11.7	14.0	11.9	12.8	9.3	12.4	11.9	8.9	8.5	10.1	7.9	6.9	6.9
EEU	3.3	8.8	6.8	8.9	6.1	6.9	6.5	6.0	4.1	8.9	8.7	5.9	6.5	9.5	6.4	6.0	5.3
IND	1.5	3.8	3.5	3.8	3.1	5.0	6.4	6.1	3.8	5.6	6.6	5.6	4.4	6.9	5.9	4.3	3.5
JPN	1.3	1.3	1.0	1.3	0.9	1.0	0.9	0.8	0.6	1.2	1.0	0.8	0.9	1.4	1.1	0.9	0.9
KOR	0.6	0.7	0.6	0.7	0.5	0.9	0.7	0.7	0.5	1.0	0.7	0.7	0.6	0.9	0.7	0.5	0.6
MEA	3.5	4.1	4.1	4.0	3.8	4.6	4.0	4.3	2.9	4.6	4.4	3.4	3.3	5.4	5.1	4.1	4.0
RAS	2.7	2.7	2.5	2.7	2.0	3.4	2.7	2.8	1.9	3.3	2.8	2.5	2.2	3.5	3.0	2.3	2.1
RUS	2.3	2.9	2.2	2.8	1.4	4.8	3.7	3.7	0.8	3.8	3.6	1.4	1.6	4.0	1.5	0.2	0.2
SAF	0.4	0.5	0.4	0.6	0.4	0.6	0.5	0.5	0.3	0.7	1.0	0.6	0.4	0.6	0.8	0.4	0.4
SAM	1.6	3.7	3.0	3.8	1.8	4.1	3.9	3.7	-0.2	5.3	5.3	1.7	-12.2	4.5	2.8	1.1	-12.5
USA	5.1	8.1	7.2	7.8	5.5	8.7	13.2	12.3	3.0	13.1	18.2	11.0	5.0	13.1	14.3	6.6	6.5
WEU	0.5	0.7	0.7	0.7	0.5	1.0	1.0	1.2	0.5	1.2	1.0	0.6	0.7	1.0	0.6	0.5	0.7

Table A 6 – Res-REF carbono intensity relative to population (tCO_{2eq}/hab)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/hab)	2010	1.5	22.6	6.6	4.6	24.7	3.4	7.2	5.7	1.2	10.2	13.0	16.5	3.3	16.1	8.4	8.1	16.2	6.1
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.7	1.0	1.2	1.0	0.9	0.9	1.3	2.2	1.5	1.0	1.1	0.9	0.7	1.0	1.0	0.9	1.0	1.2
	2030	0.7	1.2	1.2	1.5	1.0	1.1	1.6	2.5	2.1	1.0	1.1	0.8	0.8	1.3	1.1	1.9	1.4	1.6
	2040	0.9	1.2	1.2	1.2	1.6	1.5	1.6	2.1	2.2	0.9	1.3	0.8	1.0	1.7	1.1	1.8	1.3	1.9
	2050	1.1	1.4	1.5	1.3	1.6	1.5	1.5	1.9	2.4	0.9	1.4	0.7	1.0	2.2	1.2	2.0	1.3	2.4
	2060	1.2	2.0	2.1	2.0	1.5	1.6	1.5	1.8	2.7	1.0	1.6	0.7	1.0	2.3	1.2	2.4	1.6	2.7
	2070	2.7	2.2	1.7	2.1	1.7	2.2	1.6	2.4	2.6	1.3	2.0	0.7	1.0	1.8	1.3	2.6	1.8	2.8
	2080	4.4	2.4	1.9	2.3	2.6	2.3	1.7	2.4	2.8	1.3	2.1	0.7	1.0	1.3	1.2	2.4	1.9	2.7
	2090	5.3	1.6	2.0	2.1	3.0	2.3	1.7	2.4	3.0	1.5	2.2	0.7	1.1	1.3	1.2	2.2	1.9	2.6
	2100	1.7	1.3	2.0	2.0	2.8	2.0	1.8	2.7	3.5	1.9	2.3	0.8	1.2	2.0	1.3	2.3	1.8	2.9

Table A 7 - Res-REF carbono intensity relative to GDP (tCO_{2eq}/kUS$)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/kUS$)	2010	1,657.3	657.5	1,167.0	754.5	698.9	3,103.2	2,372.6	212.6	1,198.3	277.6	617.0	2,969.9	2,081.3	2,533.6	1,459.7	2,222.3	389.3	2,022.4
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.5	0.8	0.9	0.8	0.8	0.6	0.6	1.8	0.8	1.0	0.8	0.7	0.4	0.7	0.7	0.7	0.8	0.7
	2030	0.4	0.8	0.7	1.0	0.8	0.5	0.4	1.7	0.6	0.8	0.8	0.5	0.4	0.7	0.6	1.1	1.1	0.6
	2040	0.3	0.7	0.6	0.6	1.0	0.5	0.3	1.2	0.5	0.6	0.7	0.4	0.3	0.7	0.5	0.8	0.9	0.6
	2050	0.3	0.7	0.6	0.5	0.9	0.4	0.3	0.9	0.4	0.6	0.7	0.3	0.3	0.8	0.4	0.7	0.8	0.6
	2060	0.3	1.0	0.7	0.7	0.8	0.4	0.2	0.8	0.4	0.6	0.7	0.3	0.2	0.8	0.3	0.7	0.9	0.6
	2070	0.4	1.0	0.5	0.6	0.8	0.4	0.2	0.9	0.3	0.7	0.8	0.2	0.2	0.5	0.3	0.7	1.0	0.6
	2080	0.5	1.0	0.5	0.5	1.2	0.3	0.2	0.8	0.3	0.6	0.7	0.2	0.1	0.4	0.2	0.5	0.9	0.5
	2090	0.5	0.6	0.4	0.4	1.2	0.3	0.2	0.7	0.2	0.6	0.7	0.2	0.1	0.3	0.2	0.4	0.9	0.4
	2100	0.1	0.4	0.4	0.3	1.0	0.2	0.2	0.7	0.2	0.7	0.6	0.2	0.1	0.4	0.2	0.4	0.7	0.4

Table A 8 – Res-RCP60 carbono intensity relative to population (tCO_{2eq}/hab)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/hab)	2010	1.5	22.4	6.5	4.7	24.7	3.4	7.2	5.8	1.2	10.2	13.0	15.3	3.3	16.2	8.5	8.2	16.2	6.1
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.7	1.0	1.2	1.0	0.9	0.9	1.3	2.1	1.5	1.0	1.0	0.9	0.7	0.9	1.0	0.9	1.0	1.2
	2030	0.6	1.1	1.1	1.0	1.0	0.9	1.3	1.9	1.9	0.8	1.0	0.9	0.8	1.0	0.9	1.5	1.2	1.4
	2040	0.7	1.2	1.1	1.0	1.2	1.2	1.3	1.9	2.6	0.8	1.0	0.8	0.7	1.2	0.8	1.2	1.8	1.8
	2050	1.0	1.9	1.2	1.1	1.2	1.5	1.3	1.7	3.0	0.8	1.1	0.7	0.8	1.7	1.0	1.9	2.0	2.4
	2060	1.1	2.6	1.6	1.5	1.2	1.7	1.4	2.0	2.9	1.0	1.2	0.7	0.8	1.8	1.8	2.4	2.2	2.3
	2070	1.3	2.6	2.0	1.9	1.1	1.8	1.6	2.3	3.0	1.1	1.5	0.7	0.8	1.6	1.8	2.5	2.5	2.3
	2080	1.5	2.9	1.8	1.9	1.8	2.2	1.7	2.3	3.0	1.2	1.8	0.7	0.9	0.9	1.7	2.6	2.7	2.2
	2090	1.6	1.8	1.7	1.5	3.2	2.3	1.5	1.7	2.7	1.1	1.7	0.8	0.9	0.7	1.6	1.7	2.1	1.7
	2100	1.5	1.0	1.5	1.5	4.1	2.1	1.4	1.8	3.0	1.4	1.8	0.8	1.0	0.8	1.5	1.4	1.9	1.8

Table A 9 - Res-RCP60 carbono intensity relative to GDP (tCO_{2eq}/kUS$)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/kUS$)	2010	1,672.8	652.6	1,159.4	761.9	698.5	3,180.2	2,371.1	216.1	1,196.7	276.4	617.0	2,756.1	2,078.6	2,550.6	1,478.4	2,261.8	390.4	2,018.3
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.5	0.8	0.9	0.8	0.8	0.6	0.5	1.8	0.8	1.0	0.8	0.8	0.4	0.6	0.7	0.6	0.8	0.7
	2030	0.3	0.7	0.7	0.6	0.8	0.4	0.4	1.3	0.6	0.6	0.6	0.6	0.3	0.5	0.5	0.9	0.9	0.6
	2040	0.3	0.7	0.5	0.5	0.8	0.4	0.3	1.1	0.6	0.6	0.6	0.4	0.2	0.5	0.3	0.5	1.2	0.6
	2050	0.3	1.0	0.5	0.4	0.7	0.4	0.2	0.9	0.5	0.6	0.5	0.3	0.2	0.7	0.3	0.7	1.3	0.6
	2060	0.2	1.2	0.6	0.5	0.6	0.4	0.2	0.9	0.4	0.6	0.5	0.3	0.2	0.6	0.5	0.7	1.3	0.5
	2070	0.2	1.2	0.6	0.5	0.5	0.3	0.2	0.9	0.3	0.6	0.6	0.2	0.1	0.5	0.4	0.6	1.4	0.5
	2080	0.2	1.1	0.4	0.4	0.8	0.3	0.2	0.8	0.3	0.5	0.6	0.2	0.1	0.2	0.3	0.6	1.3	0.4
	2090	0.1	0.6	0.4	0.3	1.3	0.3	0.2	0.5	0.2	0.5	0.5	0.2	0.1	0.2	0.3	0.3	1.0	0.2
	2100	0.1	0.3	0.3	0.2	1.5	0.2	0.1	0.5	0.2	0.5	0.5	0.2	0.1	0.2	0.2	0.2	0.8	0.2

Table A 10 – Res-RCP45 carbono intensity relative to population (tCO_{2eq}/hab)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/hab)	2010	1.5	22.4	6.5	4.6	24.7	3.4	7.2	5.7	1.2	10.2	13.0	16.5	3.3	15.9	8.4	8.1	16.2	6.1
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.7	1.1	1.3	1.0	0.9	0.9	1.3	2.2	1.5	1.0	1.1	0.9	0.7	1.0	1.0	0.9	1.0	1.2
	2030	0.7	1.2	1.2	1.5	1.0	1.1	1.7	2.5	2.0	1.0	1.1	0.8	0.8	1.3	1.2	2.0	1.3	1.5
	2040	0.8	1.3	1.1	1.1	1.2	1.5	1.6	2.0	2.7	0.8	1.1	0.8	0.9	1.6	1.0	1.3	1.9	1.9
	2050	0.9	1.3	1.2	1.0	1.2	1.5	1.4	1.6	2.9	0.8	1.1	0.7	0.8	1.7	1.0	1.8	1.9	2.7
	2060	0.9	1.5	0.9	1.1	1.0	1.4	1.3	1.4	2.5	0.7	1.1	0.6	0.7	1.4	1.1	1.3	1.7	2.1
	2070	0.0	1.5	0.9	0.9	0.3	1.5	1.2	1.6	2.6	0.9	1.3	0.5	0.7	0.7	1.2	0.8	1.5	1.4
	2080	-2.8	1.4	1.0	1.0	1.5	1.7	1.2	1.6	2.1	1.0	1.4	0.5	0.7	0.1	0.8	0.7	1.4	1.4
	2090	-2.2	0.9	1.3	1.4	3.1	1.9	1.3	1.6	2.1	1.0	1.3	0.6	0.7	0.2	0.7	0.6	0.9	1.3
	2100	-2.4	0.7	1.6	1.4	4.5	1.9	1.2	1.7	2.2	1.2	1.3	0.6	0.8	0.1	0.8	0.6	0.9	1.4

Table A 11 - Res-RCP45 carbono intensity relative to GDP (tCO_{2eq}/kUS$)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/kUS$)	2010	1,644.3	652.6	1,157.8	754.2	698.6	3,102.3	2,375.6	212.1	1,196.7	276.4	617.0	2,970.4	2,078.6	2,507.4	1,459.7	2,220.5	389.3	2,018.3
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.5	0.8	1.0	0.8	0.8	0.6	0.6	1.8	0.8	1.0	0.8	0.7	0.4	0.7	0.7	0.7	0.8	0.7
	2030	0.4	0.8	0.8	0.9	0.8	0.5	0.5	1.7	0.6	0.9	0.8	0.5	0.4	0.7	0.6	1.1	1.0	0.6
	2040	0.3	0.7	0.6	0.6	0.8	0.5	0.3	1.2	0.6	0.6	0.6	0.4	0.3	0.7	0.4	0.6	1.3	0.6
	2050	0.3	0.7	0.5	0.4	0.7	0.4	0.2	0.8	0.5	0.5	0.5	0.3	0.2	0.7	0.3	0.7	1.2	0.7
	2060	0.2	0.7	0.3	0.4	0.5	0.3	0.2	0.6	0.3	0.4	0.5	0.2	0.1	0.5	0.3	0.4	1.0	0.5
	2070	0.0	0.7	0.3	0.2	0.1	0.3	0.2	0.6	0.3	0.5	0.5	0.2	0.1	0.2	0.3	0.2	0.8	0.3
	2080	-0.3	0.6	0.2	0.2	0.7	0.3	0.1	0.6	0.2	0.5	0.5	0.2	0.1	0.0	0.2	0.2	0.7	0.2
	2090	-0.2	0.3	0.3	0.3	1.3	0.2	0.1	0.5	0.2	0.4	0.4	0.1	0.1	0.0	0.1	0.1	0.4	0.2
	2100	-0.2	0.2	0.3	0.2	1.6	0.2	0.1	0.5	0.1	0.4	0.4	0.1	0.1	0.0	0.1	0.1	0.4	0.2

Table A 12 – Res-RCP26 carbono intensity relative to population (tCO_{2eq}/hab)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/hab)	2010	1.5	22.4	6.5	4.7	24.7	3.4	7.2	5.8	1.2	10.2	13.0	15.3	3.3	16.2	8.5	8.2	16.2	6.1
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.7	1.1	1.2	1.0	0.9	0.9	1.2	2.1	1.5	1.0	1.0	0.9	0.7	1.0	0.9	0.8	0.9	1.2
	2030	0.6	0.7	0.9	0.8	0.7	0.8	1.2	1.7	1.7	0.8	0.8	0.8	0.6	0.6	0.8	0.9	0.9	1.1
	2040	-0.3	0.5	0.9	0.5	0.7	0.9	1.0	1.2	1.7	0.6	0.7	0.6	0.6	0.4	0.5	0.4	0.5	1.2
	2050	-2.1	0.7	0.8	0.3	0.8	1.0	1.0	1.1	1.8	0.6	0.8	0.5	0.6	0.4	0.6	-0.1	0.5	1.2
	2060	-3.8	0.9	0.9	0.5	0.7	1.2	1.1	1.8	2.1	0.6	0.9	0.5	0.6	0.5	0.7	-2.6	0.5	1.5
	2070	-3.1	1.0	0.1	0.0	0.3	1.6	1.1	1.7	2.0	1.0	1.1	0.5	0.6	0.7	0.7	-5.7	0.7	1.7
	2080	-2.7	0.9	-1.3	-2.3	1.3	1.9	1.2	1.4	2.0	1.1	1.3	0.6	0.7	0.8	0.7	-5.9	0.9	1.9
	2090	-3.1	1.4	-1.6	-2.0	2.7	2.0	1.2	1.4	1.9	1.1	1.3	0.6	0.7	0.4	0.6	-6.2	0.8	2.1
	2100	-3.7	1.7	-1.5	-1.8	4.2	1.9	1.2	1.5	1.8	1.2	1.5	0.6	0.7	0.1	0.7	-6.3	0.9	1.9

Table A 13 - Res-RCP26 carbono intensity relative to GDP (tCO_{2eq}/kUS$)

Region		AFR	AUS	BRA	CAM	CAN	CAS	CHN	EEU	IND	JPN	KOR	MEA	RAS	RUS	SAF	SAM	USA	WEU
Absolute (tCO2/kUS$)	2010	1,679.2	652.6	1,159.4	761.9	698.4	3,139.7	2,369.0	217.1	1,196.7	276.4	617.0	2,761.6	2,078.6	2,548.5	1,478.4	2,265.0	390.4	2,018.3
Relative to 2010	2010	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2020	0.5	0.8	0.9	0.8	0.8	0.6	0.5	1.8	0.7	1.0	0.8	0.8	0.4	0.6	0.7	0.6	0.8	0.7
	2030	0.3	0.5	0.6	0.5	0.5	0.4	0.3	1.1	0.5	0.6	0.5	0.5	0.3	0.3	0.4	0.5	0.7	0.5
	2040	-0.1	0.3	0.5	0.3	0.5	0.3	0.2	0.7	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.3	0.4
	2050	-0.6	0.4	0.3	0.1	0.4	0.3	0.2	0.5	0.3	0.4	0.4	0.2	0.1	0.1	0.2	0.0	0.3	0.3
	2060	-0.8	0.4	0.3	0.2	0.4	0.3	0.2	0.8	0.3	0.4	0.4	0.2	0.1	0.2	0.2	-0.8	0.3	0.3
	2070	-0.5	0.4	0.0	0.0	0.1	0.3	0.1	0.7	0.2	0.5	0.4	0.2	0.1	0.2	0.2	-1.5	0.4	0.3
	2080	-0.3	0.4	-0.3	-0.5	0.6	0.3	0.1	0.5	0.2	0.5	0.4	0.2	0.1	0.2	0.1	-1.3	0.4	0.3
	2090	-0.3	0.5	-0.3	-0.4	1.1	0.2	0.1	0.4	0.1	0.5	0.4	0.1	0.1	0.1	0.1	-1.1	0.4	0.3
	2100	-0.3	0.6	-0.3	-0.3	1.5	0.2	0.1	0.4	0.1	0.4	0.4	0.1	0.1	0.0	0.1	-1.0	0.4	0.2

12.Annex 3 –Constraints description

This annex presents additional detailed data on the mathematical constraints used in the model and presented in chapter 7. Table A 14 and Table A 15 complement each other (as part 1 and part 2) of the constraints for the Energy System.

Table A 14 – Constraint description for the Energy System (part 1)

Group	TAG	Description
CO2 Injection on Oil Fields	OONA	CO2 Injection on Onshore Oil Reservoirs at 100 km from source
	OONB	CO2 Injection on Onshore Oil Reservoirs at 500 km from source
	OONC	CO2 Injection on Onshore Oil Reservoirs at 1000 km from source
	OOND	CO2 Injection on Onshore Oil Reservoirs at 2000 km from source
	OOFA	CO2 Injection on Offshore Oil Reservoirs at 100 km from source
	OOFB	CO2 Injection on Offshore Oil Reservoirs at 500 km from source
	OOFC	CO2 Injection on Offshore Oil Reservoirs at 1000 km from source
	OOFD	CO2 Injection on Offshore Oil Reservoirs at 2000 km from source
CO2 Injection on Gas Fields	GONA	CO2 Injection on Onshore Gas Reservoirs at 100 km from source
	GONB	CO2 Injection on Onshore Gas Reservoirs at 500 km from source
	GONC	CO2 Injection on Onshore Gas Reservoirs at 1000 km from source
	GOND	CO2 Injection on Onshore Gas Reservoirs at 2000 km from source
	GOFA	CO2 Injection on Offshore Gas Reservoirs at 100 km from source
	GOFB	CO2 Injection on Offshore Gas Reservoirs at 500 km from source
	GOFC	CO2 Injection on Offshore Gas Reservoirs at 1000 km from source
	GOFD	CO2 Injection on Offshore Gas Reservoirs at 2000 km from source
CO2 Injection on Low Cost Aquifers	LONA	CO2 Injection on Onshore Low Cost Aquifers at 100 km from source
	LONB	CO2 Injection on Onshore Low Cost Aquifers at 500 km from source
	LONC	CO2 Injection on Onshore Low Cost Aquifers at 1000 km from source
	LOND	CO2 Injection on Onshore Low Cost Aquifers at 2000 km from source
	LOFA	CO2 Injection on Offshore Low Cost Aquifers at 100 km from source
	LOFB	CO2 Injection on Offshore Low Cost Aquifers at 500 km from source
	LOFC	CO2 Injection on Offshore Low Cost Aquifers at 1000 km from source
	LOFD	CO2 Injection on Offshore Low Cost Aquifers at 2000 km from source
CO2 Injection on High Cost Aquifers	HONA	CO2 Injection on Onshore High Cost Aquifers at 100 km from source
	HONB	CO2 Injection on Onshore High Cost Aquifers at 500 km from source
	HONC	CO2 Injection on Onshore High Cost Aquifers at 1000 km from source
	HOND	CO2 Injection on Onshore High Cost Aquifers at 2000 km from source
	HOFA	CO2 Injection on Offshore High Cost Aquifers at 100 km from source
	HOFB	CO2 Injection on Offshore High Cost Aquifers at 500 km from source
	HOFC	CO2 Injection on Offshore High Cost Aquifers at 1000 km from source
	HOFD	CO2 Injection on Offshore High Cost Aquifers at 2000 km from source

Table A 15 – Constraint description for the Energy System (part 2)

Group	TAG	Description
Balance between captured CO2 and Injected CO2	CCBT	Balance of Captured CO2 for Transport
	ORNA	Balance between Captured CO2 for Onshore EOR at 100 km
	ORNB	Balance between Captured CO2 for Onshore EOR at 500 km
	ORNC	Balance between Captured CO2 for Onshore EOR at 1000 km
	ORND	Balance between Captured CO2 for Onshore EOR at 2000 km
	ORFA	Balance between Captured CO2 for Offshore EOR at 100 km
	ORFB	Balance between Captured CO2 for Offshore EOR at 500 km
	ORFC	Balance between Captured CO2 for Offshore EOR at 1000 km
	ORFD	Balance between Captured CO2 for Offshore EOR at 2000 km
	GRNA	Balance between Captured CO2 for Onshore Gas at 100 km
	GRNB	Balance between Captured CO2 for Onshore Gas at 500 km
	GRNC	Balance between Captured CO2 for Onshore Gas at 1000 km
	GRND	Balance between Captured CO2 for Onshore Gas at 2000 km
	GRFA	Balance between Captured CO2 for Offshore Gas at 100 km
	GRFB	Balance between Captured CO2 for Offshore Gas at 500 km
	GRFC	Balance between Captured CO2 for Offshore Gas at 1000 km
	GRFD	Balance between Captured CO2 for Offshore Gas at 2000 km
Uranium Storage	URSA	Uranium Storage - Depleted Uranium from 0.0072 enrichment.
	URSB	Uranium Storage - Depleted Uranium from 0.0085 enrichment.
	URSC	Uranium Storage - Depleted Uranium from 0.02 enrichment.
	URSD	Uranium Storage - Depleted Uranium from 0.035 enrichment.
	URSE	Uranium Storage - Depleted Uranium from 0.045 enrichment.
	URSF	Uranium Storage - Depleted Uranium from 0.08 enrichment.
	URSG	Uranium Storage - Depleted Uranium from 0.2 enrichment.
	URSZ	Uranium Storage - Depleted Uranium from other process.
Extraction or production	OEUP	Constraint on maximum oil extraction and production.
	GEUP	Constraint on maximum oil extraction and production.
	CEUP	Constraint on maximum coal extraction and production.
	UEUP	Constraint on maximum uranium extraction and production.
Power Sector	FXRN	Constaint for accounting flexible capacity and intermitent capacity
	INTE	Constaint on maximum addition of intermitent sources
Import/ Export	ENBL	Constaint for accounting energy balance of imports and exports
GHG Emission	CO2	Energy related CO2 emissions (kt)
	CO2P	Process related CO2 emissions (kt)
	CH4	Energy related CH4 emissions (kt)
	N2O	Energy related N2O emissions (kt)
	CO2L	Energy related CO2 emissions (kt)
	CH4L	Energy related CH4 emissions (kt)
	N2OL	Energy related N2O emissions (kt)
	GHG	Total GHG emissions (kt)
CCS	FCCS	Accounting for Fossil-CCS (kt)
	BCCS	Accounting for Bio-CCS (kt)

As shown, all 32 constraints of Table A 14 are related to limiting the CO_2 injection on each of the reservoirs categories used. Also related to CCS are the first 16 constraints of Table A 15, which is responsible for accounting the balance between captured CO_2 and injected CO_2, for all three categories of distance of reservoirs used in the model.

The remaining constraints are responsible for accouting the storage of spent uranium (8), limiting the extraction and production of primary energy sources (4), both for scenario building and for fitting base year purposes. There are also two constraints for dealing with flexible and intermitent sources of electricity and their balance in the transmition and distribuition activities.

Finally, the last 10 constraints of Table A 15 are related to GHG emission profile of each region. In these, there constraint for accounting the CO_2, CH_4 and N_2O emissions of the Energy and Land Systems. One constraint is responsible for accounting the total GHG emissions, i.e., the weighted sum of the GHG in regards to the GWP. The last two constraints are responsible for accounting the capture of carbon dioxide, according to the source: fossil (FCCS) or biomass (BCCS).

As mentioned in the chapter 7, there are 735 constrains to create and regulate the land categories and land changes allowed in the developed model. Table A 16, below, presents an example for the constrains added for the Forest land cover, at the category A (as explained in chapter 6). For each of the 7 land covers and 7 categories, there are 15 constrains: one for each ime step within the model that accounts for land cover changes, and one which presents the total at a given year.

Table A 16 – Constraint description for the Land System (e.g. for Forest type A)

Group	TAG	Description
Balance of Forest A for time periods	BFAT	Balance of Forest A Total
	BFAa	Balance of Forest A for time period 2010
	BFAb	Balance of Forest A for time period 2015
	BFAc	Balance of Forest A for time period 2020
	BFAd	Balance of Forest A for time period 2025
	BFAe	Balance of Forest A for time period 2030
	BFAf	Balance of Forest A for time period 2035
	BFAg	Balance of Forest A for time period 2035
	BFAh	Balance of Forest A for time period 2045
	BFAi	Balance of Forest A for time period 2050
	BFAj	Balance of Forest A for time period 2060
	BFAk	Balance of Forest A for time period 2070
	BFAl	Balance of Forest A for time period 2080
	BFAm	Balance of Forest A for time period 2090
	BFAn	Balance of Forest A for time period 2100