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TEMPORAL ISSUES IN MITIGATION ALTERNATIVES FOR THE ENERGY SECTOR IN BRAZIL

Larissa Pupo Nogueira de Oliveira

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: Roberto Schaeffer
Alexandre Salem Szklo

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Examinada por:

Prof. Roberto Schaeffer, Ph.D.

Prof. Alexandre Salem Szklo, D.Sc.

Prof. André Frossard Pereira de Lucena, D.Sc.

Prof. Suzana Kahn Ribeiro, D.Sc.

Prof. Angelo Costa Gurgel, D.Sc.

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A Giullia e a Luiz Felipe.

“The shift to a cleaner energy economy won’t happen overnight,
and it will require tough choices along the way.
But the debate is settled. Climate change is a fact.”

Barack Obama

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QUESTÕES TEMPORAIS EM ALTERNATIVAS DE MITIGAÇÃO PARA O SETOR ENERGÉTICO NO BRASIL

Larissa Pupo Nogueira de Oliveira

Março/2016

Orientadores: Roberto Schaeffer
Alexandre Salem Szklo

Programa: Planejamento Energético

A preferência temporal é uma questão crítica no debate sobre mudanças climáticas, pois esta é um problema de longo prazo que requer investimentos no curto prazo. Nesse contexto, a escolha da taxa de desconto é crucial por causa da questão intergeracional, que coloca a escolha entre investir ou não em mitigação hoje para proteger gerações futuras de impactos. Além disso, o trancamento tecnológico e a configuração dos acordos globais de mitigação também influenciam o momento de investimento. No entanto, pouco se tem discutido sobre o impacto de questões temporais sobre cenários energéticos. Essa tese objetiva preencher essa lacuna pela avaliação e comparação de um conjunto de cenários com três diferentes taxas de desconto e diferentes premissas de antecipação e tempo de políticas de baixo carbono. Para isso, o modelo de otimização TIMES foi adotado e dezesseis cenários foram gerados para que se pudesse identificar diferenças entre *mix* tecnológico, custo de políticas e custo de CO_2. Os resultados mostram que questões temporais podem influenciar significativamente o perfil tecnológico, favorecendo mais ou menos fontes renováveis de energia em detrimento a tecnologias de captura.

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

TEMPORAL ISSUES IN MITIGATION ALTERNATIVES FOR THE ENERGY SECTOR IN BRAZIL

Larissa Pupo Nogueira de Oliveira

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Advisors: Roberto Schaeffer
Alexandre Salem Szklo

Department: Energy Planning

Time preference is a crucial issue in the climate change debate, since it is a long term problem that requires short term action. Discount rate choice is critical since intergenerational issues imposes choices between investing or not in greenhouse gases mitigation today on to protect future generations from impacts. Furthermore, technological lock-in and the configuration of global mitigation agreements are also issues that influence when to invest. Today, the integrated assessment of climate policies on energy systems has been used as a key tool to evaluate impacts and technology pathways in the long term, but little attention has been given to timing issues and how they might impact scenario results. This thesis aims at filling this gap by evaluating and comparing scenarios with three distinct discount rates and different timing and foresight premises of low carbon policies on Brazil’s energy system. To that purpose, the integrated assessment model TIMES was adopted in order to optimize Brazil’s energy system. Sixteen scenarios were generated and differences regarding technology pathways, total cost of system and carbon price were assessed. Results show that elements of time preference may indeed change technology profile of low carbon policies, favoring more or less renewable technologies over carbon capture and storage.

Contents

List of Figures

List of Figures in Annex A

List of Tables

List of Acronyms

AFOLU	Agriculture, Forestry and Other Land Use
AMPERE	Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
ANEEL	Agência Nacional de Energia Elétrica
ANP	Agência Nacional de Petróleo, Gás e Biocombustíveis
BCB	Banco Central do Brasil
BECCS	Bio-energy with carbon capture and storage
BIG-CCGT	Biomass integrated gasification with combined cycle gas turbines
bioCCS	Bio-energy with carbon capture and storage
BRICS	Brasil, Rússia, Índia, China e África do Sul
C2ES	Center for Climate and Energy Solutions
CAPM	Capital Asset Pricing Model
CBA	Cost Benefit Analisys
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CEBDS	Conselho Empresarial Brasileiro para o Desenvolvimento Sustentável
CEST	Condensing-extraction steam turbine
CGE	Computable General Equilibrium
CIMGC	Comissão Interministerial de Mudança Global do Clima
CO2	Dióxido de Carbono
COMPERJ	Complexo Petroquímico do Estado do Rio de Janeiro
COP	Conference of the Parties
CSP	Concentrated Solar Power
DDR	Declining Discount Rate
DDRS	Declining Discount Rate per Sector
EC	European Comission
EFOM	Energy Flow Optimization Model
EMF	Energy Modelling Forum
EPE	Empresa de Pesquisa Energética
etOH	Ethanol
ETS	European Trading Scheme
ETSAP	Energy Technology System Analysis Programme
FT	Fischer-Tropsch
GDP	Gross Domestic Product
Gg	Giga-gram
GHG	Greenhouse Gas
Gt	Giga-ton
GTL	Gas-to-Liquids
H2	Hydrogen

HHSS	Household and Services
IAM	Integrated Assessment Model
IBGE	Instituto Brasileiro de Geografia e Estatística
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IMF	International Monetary Fund
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
IRENA	The International Renewable Energy Agency
ITMO	Internationally Transferred Mitigation Outcomes
LC	Low Carbon
LNG	Liquefied Natural Gas
M	Myopic
MARKAL	Market Allocation
MCTI	Ministério de Ciência, Tecnologia e Inovação
MD	Myopic + Delayed
MESSAGE	Model for Energy Supply Systems And their General Environmental impact
MKT	Market
MMA	Ministério de Meio Ambiente
MME	Ministério de Minas e Energia
MSW	Municipal Solid Waste
Mt	Mega-ton
MW	Megawatt
NG	Natural Gas
NGPU	Natural Gas Processing Unit
NPCC	National Plan on Climate Change
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
p.y.	per year
PBL	Planbureau voor de Leefomgeving
PDF	probability density function
PF	Perfect Foresight
PFD	Perfect Foresight + Delayed
PP	Power Plant
PPA	Power Purchase Agreement
R&D	Research and Development
REIDI	Regime especial de incentivos para o desenvolvimento da infraestrutura
RNEST	Refinaria Abreu e Lima
SATIM	South African TIMES
SOC	Social

TIC	Techno-institutional Complex
TIMBRA	TIMES Brazil
TIMES	The Integrated MARKAL-EFOM System
TIS	Technical Innovation System
TWh	Terawatt-hour
UFRJ	Universidade Federal do Rio de Janeiro
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
USW	Urban Solid Waste
WACC	Weighted Average Cost Of Capital
WEO	World Energy Outlook
WITCH	World Induced Technical Change Hybrid model
WRI	World Resource Institute

1 Introduction

Climate change mitigation has been brought into light because of the potential risks and damages global warming may cause if not controlled. The most recent Conference (COP-21, in Paris) about climate change set, for the first time, a global agreement on greenhouse gas (GHG) emission reductions worldwide, with the main goal of keeping average temperature raise under 2^{o}C.

In order to deal with the climate change issue and stabilizing greenhouse gas concentrations by reducing GHG emissions globally, a great effort should be placed on the transformation of human societies, from the way it produces and consumes energy to how it uses land surface (Clarke et al. 2014).

Some questions under this debate might emerge and need to be answered: what are the choices that lead to the optimal transformation pathway? These choices refer to the establishment of the goal in terms of emission reduction, the definition of how to reach this goal, i.e., the transformation pathway itself, the technologies used for mitigation and sectors involved in this effort. Also, how could actions taken today influence future generations in terms of costs and benefits? Discussions about how to answer these questions are qualitative and quantitative, and proper evidence on how to reach specific goals is commonly based on scenario making.

In fact, the concept of scenarios has been, for years, employed in low-carbon policy studies and applications have ranged from providing future global GHG levels to underpinning long-term national energy policy initiatives and to assessing the implications of scenarios for particular national energy systems (Hughes & Strachan 2010).

Moreover, the transformation pathway towards a low carbon economy is latent in policy discussions and international negotiations. Under this debate, scientific community seeks to answer these questions and to give support to policymakers through a wide range of projections, pathway simulations and scenario analysis (Giannakidis et al. 2015). This includes using tools such as energy systems models that depict energy systems in order to evaluate technological transitions under different sets of policies. The importance of considering energy systems models relies in the fact that globally this system (which includes supply and consumption) is the main responsible for GHG emissions[1], but the modeling framework may also contemplate important sectors in the climate change debate, such as the AFOLU[2].

In fact, Fais and Blesl (2015) affirm that energy systems analysis has been playing an important role in supporting political decision-making process through the identification of sustainable technology pathways and through the comparison of different energy scenarios in order to assess alternative pathways towards sustainability. Moreover, energy policy and planning are gaining complexity and uncertainty since direct energy issues like the availability of primary energy sources are coupled with other external issues like environment, GHG emissions, security of supply and risk (Giannakidis et al. 2015).

The need for detailed studies, roadmaps and scenarios related to climate policy mitigation comes from the glimpse of a low carbon (or even carbon-free) energy system. Main parameters of technologies, such as efficiencies, costs and the moment of introduction have high uncertainties (Giannakidis et al. 2015). In the climate change area, studies like van der Zwaan et al. (2015); Kober et al. (2016); and Lucena et al. (2015) are a few examples of recent assessments of energy technology development under climate change mitigation efforts.

In general, climate change related studies with scenario modeling evaluate the impact of different climate policies, like a carbon tax or a cap in emissions, both market mechanisms to stimulate GHG emissions reduction (Nogueira et al. 2014; Lucena et al. 2015; Clarke et al. 2009). Sensitivities are commonly related to policy stringency, type of policy (Fais and Blesl 2015) or technology profile (Malagueta et al. 2013).

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[1] IPCC (2014) shows that in 2010 economic sectors such as industry, transportation, buildings summed up with electricity and heat production emitted 66% of global emissions in 2010.

[2] Agriculture, forestry and other land use.

As Kolstad et al. (2014), pp. 228, affirm, ‘in climate change decisions, aggregating the pros and cons of alternative actions is particularly difficult because most benefits of mitigation will materialize only in the distant future. On the other hand, the costs of mitigation are borne today.’ Indeed, investing in climate change mitigation is an intertemporal decision, since it depends on the weight the decision maker puts on the welfare of future generations. On the other side, when deciding about low carbon technologies to invest, issues like the opportunity cost of the technology and investment risk also arise, influencing the decision process.

In that context, one parameter that could make a big difference when evaluating low carbon scenarios is the discount rate, which is the main indicator of an agent’s behavior in terms of time preference and risk aversion. In fact, an important debate in economics triggered by the Stern Review (Stern 2007) has centered on the discount rate that should be applied in evaluating climate change impacts and mitigation costs (Nordhaus 2007; Stern 2008; Dasgupta 2008; Smith 2010; Quiggin 2008).

Moreover, studies like Stern (2007) and Nordhaus (2007) adopted integrated assessment models to evaluate monetary losses and damages arising from climate change and they discuss discount rate choice under that framework, since the debate is essentially on economics. However, lack of attention has been given to how discount rate choice might affect the investment choice in terms of technology in order to face the climate change issue. The discussion regarding technology choice is important because: (i) low carbon technologies have different profiles, efficiencies and costs (of capital or operational) and there should be technology mixes that lead to the least cost energy system and to the lower GHG emission profile in the long-term; (ii) the choice between these mixes, however, should be intrinsically related to the agent’s perspective on different elements, such as time preference, risk and access to capital; (iii) an important part of the climate change mitigation action is establishing stimulus to these low carbon technologies through the conception and implementation of policies to promote technology viability (iv) the orientation of these policies should be based on robust evidence on best option in terms of technological pathways; (v) the choice of an adequate policy and of an adequate technology portfolio to promote relies, among other elements, on bridging the gap between agents responsible for investing their money in low carbon technologies (the private perspective) and agents worried about economic development without harming the welfare of future generations (the social perspective).

In addition to the discount rate choices, there are also other elements influencing investment decision in terms of timing, i.e., the moment of the investment decision. The lock-in effect[3], for example, might not be only technological, but also institutional and it causes an inertia in the energy system, possibly delaying investments that require a significant change in the system (Unruh 2000; Foxon 2002; Perkins 2003). That is true for the energy system and investments that require any king of disruption, as the reconfiguration of the electrical grid or the modification of motor engines, as the case of renewable energy and electric vehicles, respectively. Thus, another issue that has critical influence in the investment decision either in terms of intensity and timing is the contour of international negotiations and commitments regarding climate change. This has to do with the asymmetric distribution of responsibilities in terms of past emissions and future mitigation and also with the financial capacity of distinct countries to commit to higher levels of emission abatement (Luderer et al. 2013; Tavoni et al. 2013; Bosetti et al. 2009). This fragmented configuration of global commitments might lead to lower level of commitments assumed by non-developed countries, even incurring in delayed action.

The main goal of this thesis is addressing this knowledge gap by adopting energy systems modeling to evaluate how timing issues, mainly related to different perspectives on discount rate choice plus other elements that might influence time preference, may impact transitions in technological pathways in Brazil's energy system. The main question the thesis seeks to answer is: how aspects that influence time preference in terms of low carbon investment may influence energy transition pathway towards a low carbon economy in Brazil? The originality of this thesis relies in the fact that it is the first study attempting to

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[3] Lock in effect is defined as the continued use of a range of supposedly inferior technologies (Perkins 2003).

add the element of time preference to the climate change debate under an integrated energy system modeling approach and to apply it to Brazil’s case.

The importance of establishing a national frontier of analysis and applying the methodology to Brazil’s energy system to evaluate low carbon policies under different premises of time preference comes from the fact that Brazil has recently engaged in mandatory emission reduction targets towards UNFCCC (United Nations Framework Convention on Climate Change) and it will have to decide on how to reach these targets either in terms of where to invest (technological pathway) and how to promote transition (policy choice). Energy sector should play a relevant part on this transition and should not be underrated, since its participation on national emissions has raised in the last few years and it is facing issues regarding the remaining hydropower potential, which is scarce, and the need to put into production recently discovered subsalt oil resources. These factors combined with the increasing energy demand in the country due to economic growth should incur in a progressive increment in GHG emissions in the sector in the medium and long-term, if no action is taken to avoid it (Nogueira et al. 2014; Lucena et al. 2015).

Also, Brazil, as a developing country, currently incurs in high discount rates, but in the medium to long-term, as the country reaches economic development, these rates might change and suffer a reduction, possibly reaching the level of developed countries. This would basically depend on issues related to the perception of risk, to the removal of market failures and to the provision of access to capital. Hence, the analysis of different patterns of discount rates and their impacts on the mix energy supply should also give an overview of possible energy futures for Brazil, helping agents (policymakers and investors) with robust information on possible consequences of different development profiles.

Moreover, as climate change mitigation is a matter of time preference, evaluating distinct discount rates in association with climate change policy is an exercise of assessing different time preference choices in pursuit of a low carbon economy. The combination of distinct discount rate with distinct premises of foresight and global climate change agreements result in a set of scenarios that should provide insights on the consequences of different climate action profiles on the energy system. In that context, results should establish a good base for policymakers to decide about promoting policies for a sustainable future through incentivizing investment in low carbon technologies.

For the purpose of this thesis, three discount rates profiles were adopted in combination with cap-based low carbon policies to originate sixteen scenarios to be assessed. Besides, it was also considered scenarios with myopic vision in opposition to scenarios with perfect foresight, in order to reflect the effects of technological lock-in, and scenarios with delayed action in terms of mitigation in opposition to early action scenarios, in order to reflect different configurations of global climate change agreements. All definitions of scenarios are detailed in chapter four. These scenarios aim at testing the hypothesis that parameters that influence the moment of investment do play an important role when establishing low carbon scenarios and, consequently, it has great influence on technological pathway.

This thesis is divided in six parts: the first one is this introduction to the thesis; chapter two gives an overview on low carbon policies, contextualizing the climate change debate by resuming recent history on global climate change agreements, exposing the main policy mechanisms to promote mitigation mainly in the energy sector and giving a prospect of current status for Brazil; chapter three, in turn, discusses the role of discount rate in cost-benefit analysis and also focus on the intergenerational issue brought up by discount rate choice when evaluating investments in mitigation action; chapter four details the methodology proposed in the thesis, presents the modeling tool (the Integrated Markal EFOM System – TIMES model) adopted, as well as how it was modeled to reflect the Brazilian energy system. It also explains premises adopted in terms of discount rates, climate policies, economic growth, etc; chapter five presents the main results of scenario runs, exposing the effect of discount rates and climate policies on the energy system; finally, chapter six summarizes the main conclusions of this work and also discusses future works that could arise from this thesis.

2 Low Carbon Policies: Context, Mechanisms and Current Status

Global climate change constitutes a threat to not only human’s well-being, but also to other living things. The impact on ecosystem functioning, biodiversity, capital productivity and human health has led to the development of studies on climate change economics in order to generate insights and empirical evidence on policy design (Goulder and Pizer 2006). According to IPCC’s fifth Assessment Report (IPCC 2013), climate change is leading to a drop on agricultural yields in tropical and sub-tropical regions; to the spread of diseases carried by vectors like mosquitoes, to the exposition of water stress, to more intense weather-related disasters and to extinctions of plant and animal species. Henceforth, the main goals are reducing GHG emissions and avoiding negative impacts without compromising economies worldwide, also keeping the development of non-developed nations sustainable.

Today, the climate change debate is a major scientific and public policy issue. Although there have been disagreements about the adoption of low carbon policies by nations, it has been possible to observe the emergence of climate change policies in many developed and under development nations (Goulder and Pizer 2006). The most recent landmark regarding global commitment on CO_2 mitigation is the Paris Agreement, signed at COP-21 in December of 2015. It has established a legally binding and universal agreement on climate aiming at avoiding global warming superior to 2^oC.

Although no solid action has yet been established by the Agreement, Nachmany et al. (2015) affirm that the pace of climate actions among countries has been positive in the last few years: the number of climate-related laws worldwide has nearly doubled from 426 in 2009 to 804 at the end of 2014; the study (Nachmany et al. 2015) covers 99 countries and, among them, almost half of them has emission reduction targets up to 2020; over 75% of global emissions are subject to an economy-wide reduction target; and while eight out of ten countries have a renewable energy target, nine out of them have low-carbon technologies promotion targets.

Indeed, the stock of climate laws doubled between 2005 and 2009 and then doubled again between 2009 and 2014, as shown in Figure 2-1[4]. At the end of 2014, according to Nachmany et al. (2015), there were more than 800 climate-related laws effective in the 99 countries considered by the study. These 99 countries can be seen in Figure 2-2, that also exposes the quantity range of laws adopted in each country.

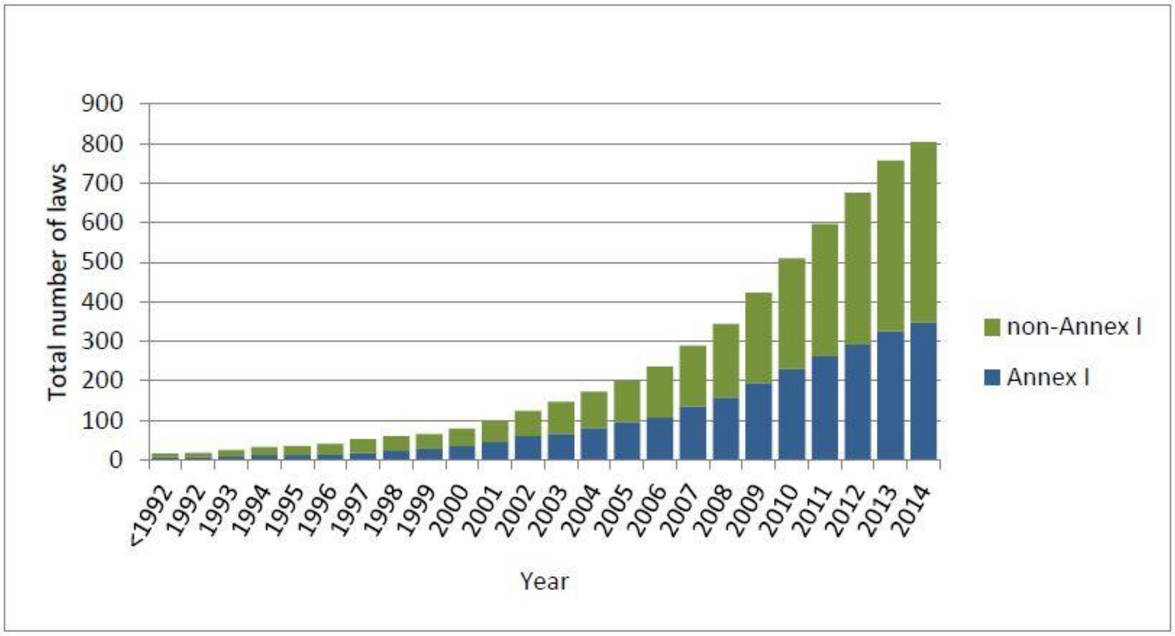

Figure 2-1 – Stock of climate change legislation by the end of 2014.

Source: Nachmany et al. (2015).

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[4] Figure divides countries in Annex I and non-Annex I countries according to their attribution under Kyoto Protocol: Annex I countries committed with mandatory reduction targets while non-Annex I countries committed with voluntary reduction targets.

Figure 2-2 – Climate change-related legislation in 99 countries, 2014.

Source: Nachmany et al. (2015).

The year of 2015 kept the trend related to carbon policy. Probably the most important climate-related policy enforcement was the approval of the “Planning for Federal Sustainability in the Next Decade” by United States Government. After years reluctant in committing to climate change mitigation actions[5], the country set a new target for the federal government’s greenhouse gas emissions to be reduced by 40% by 2025 against 2008 levels (White House 2015; Nachmany et al. 2015). Besides, it should be mentioned that BRICS countries such as China, India and Brazil also demonstrated interest in committing to reduction targets, after years attached only to voluntary targets.

As the climate change issue gains more space in public policy agenda, it becomes important to understand its background and the main mechanisms adopted in order to constraint CO_2 emissions of a country or a region. In this sense, it is possible to understand how climate change policies become effective and to map strengths and weaknesses of each mechanism. This is relevant in the sense that, for this thesis, different policy mechanisms will be tested in an integrated modeling approach and each of them might lead to different

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[5] The country withdrew from the Kyoto Protocol in 2001.

scenarios results. Moreover, the understanding of each policy instrument will be useful to interpret the outcomes.

Hence, in this chapter the history of climate change agreements will be exposed in order to point out the recent global efforts in terms of low carbon policies and the context in which Brazil is inserted as a nation aiming at engaging in emissions targets. The main mechanisms, such as carbon tax and cap-and-trade system, will be discussed aiming at evidencing the main tools of public policy in climate change. At last, Brazil's current status as a nation committed with climate change mitigation will be described by indicating who drives climate policy in Brazil and discussing the latest commitment Brazil has engaged to during COP-21 in Paris.

2.1 History

The first important treaty signed in order to limit climate change occurred in 1992 at the Rio Convention, when the United Nations Framework Convention on Climate Change, the UNFCCC, was founded. The main objective of the UNFCCC is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 2016a). In 1995, participating countries launched negotiations to strengthen the response to climate change and two years later, in 1997, the Kyoto Protocol was adopted (UNFCCC 2016b).

As detailed in UNFCCC (2016c) The Kyoto Protocol is an international agreement that commits its Parties (countries that joined the agreement) by setting international binding emission reduction targets. Although it was signed in 1997, it became effective only in 2005 and its first commitment period was between 2008 and 2012.

The first commitment period included 37 industrialized countries and the European Community. The target was reducing GHG emissions to an average of 5% against 1990 levels. In 2012, at the Doha Climate Change Conference (COP18), the Protocol was amended with new commitments between 2013 and 2020 for Annex I Parties, i.e., developed countries that had already committed to mandatory reduction targets[6]. The second commitment established reduction targets equivalent to at least 18% below 1990 levels until 2020 (UNFCCC 2016c).

Emission reduction targets are national and, in absolute terms, vary according to the Parties. Moreover, UNFCCC (2016c) shows three market-based mechanisms that helps Annex I countries to achieve their targets:

a) International Emissions Trading: parties that committed to Kyoto Protocol have reduction emission targets or a maximum level of allowed emissions. An Emission trading scheme allows countries with spare emissions to sell this excess to countries that are over their targets (UNFCCC 2016d). This scheme will be better detailed in the next item of the chapter, since until today it plays an important role as a low carbon policy mechanism.
b) Clean Development Mechanism (CDM): allows a country with an emission reduction target to implement mitigation projects in developing countries with no reduction commitment. It is an emission offset instrument, since these mitigation projects may earn saleable certified emission reduction credits to be counted towards meeting Kyoto targets (UNFCCC 2016e).
c) Joint Implementation: allows a country with an emission reduction commitment to implement a mitigation project outside its borders, in another country with reduction commitments. The emission reduction may count towards meeting the Kyoto target of the investing country as the country that receives the investment enjoys foreign investment and technology transfer (UNFCCC 2016f)

These mechanisms were broadly adopted in the last years and they constituted an important step towards a global reduction regime (UNFCCC 2016c), but it is important to mention that it was not a global agreement since signatory Parties did not include important

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[6] Although composition of Parties in the second commitment has changed compared to the first commitment.

countries, such as United States, Japan, Russia and Canada (Viola & Basso 2015). Besides, developing countries like Brazil did not commit to mandatory targets.

Since then, incremental steps have been taken in order to strengthen and to improve commitments. In 2009, at COP15 in Copenhagen, for the first time it was agreed among Parties to limit global warming to 2ºC, although no new international agreement was signed (COP21 2016). Only in 2011, at Durban Convention, the first effort to produce a new protocol was made. At COP19 in Warsaw, in 2013, Parties were invited to start preparing for their Intended Nationally Determined Contributions (INDCs) in order to establish how they could contribute to the new climate agreement in a clear, transparent and understandable way (Paris Climat 2015 2016).

This new agreement on climate change mitigation that would include periods after 2020 was launched, indeed, in 2015, at COP21, in Paris (COP21 2016). According to European Commission (EC 2016), 195 countries adopted the “first-ever universal and legally-binding global climate deal”. According to the agreement (UNFCCC 2015), governments agree to make a joint effort aiming at keeping global average temperature raise well below 2ºC in relation to pre-industrial levels, putting as a long term goal an increase limit of 1.5ºC in order to reduce risks and impacts of climate change. Governments also acknowledge that global emissions should peak as soon as possible and that it should take longer to occur in developing countries. Moreover, the agreement should lead governments to undertake rapid emission reductions thereafter in accordance with the best available science.

There are also transparency goals in the agreement in order to make it possible to follow up its execution. UNFCCC (2015) states that governments agree to reunite and discuss targets (INDCs) every 5 years in order to make them more ambitious, agree to report to regularly the execution of the targets either to other Parties or to the public and agree to adopt a transparent and robust accountability system.

However, although the agreement urges for ambitious action, Olhoff et al. (2015), UNFCCC (2015), EC (2016a) and PBL (2016) affirm that INDCs submitted by the Parties are not enough to put the world on a cost-effective pathway towards the increase limit below

$2^{o}C$ of global average temperature. PBL (2016) shows that, once implemented, conditional and unconditional INDCs should lead to a 9 and a 11 $GtCO_2e$ emission reduction, respectively. Therefore, given the need to reduce emissions in 23 $GtCO_2e$ in order to fulfill the $2^{o}C$ target, INDCs would still leave a gap of 14 $GtCO_2e$ relative to the global emission level requirement. Olhoff et al. (2015) also say that the median emission level in 2030 in scenarios with a probability of keeping temperature increase to below $2^{o}C$ by the end of the century higher than 66% is 42 $GtCO_2e$ and the similar level for a $1.5^{o}C$ pathway is 30 $GtCO_2e$. Figure 2-3 illustrates what was just discussed: it can be observed the emission gap given by the difference between the emission levels for 2025 and 2030 that would be consistent with achieving the climate target of below $2^{o}C$ and the levels projected to result from INDCs.

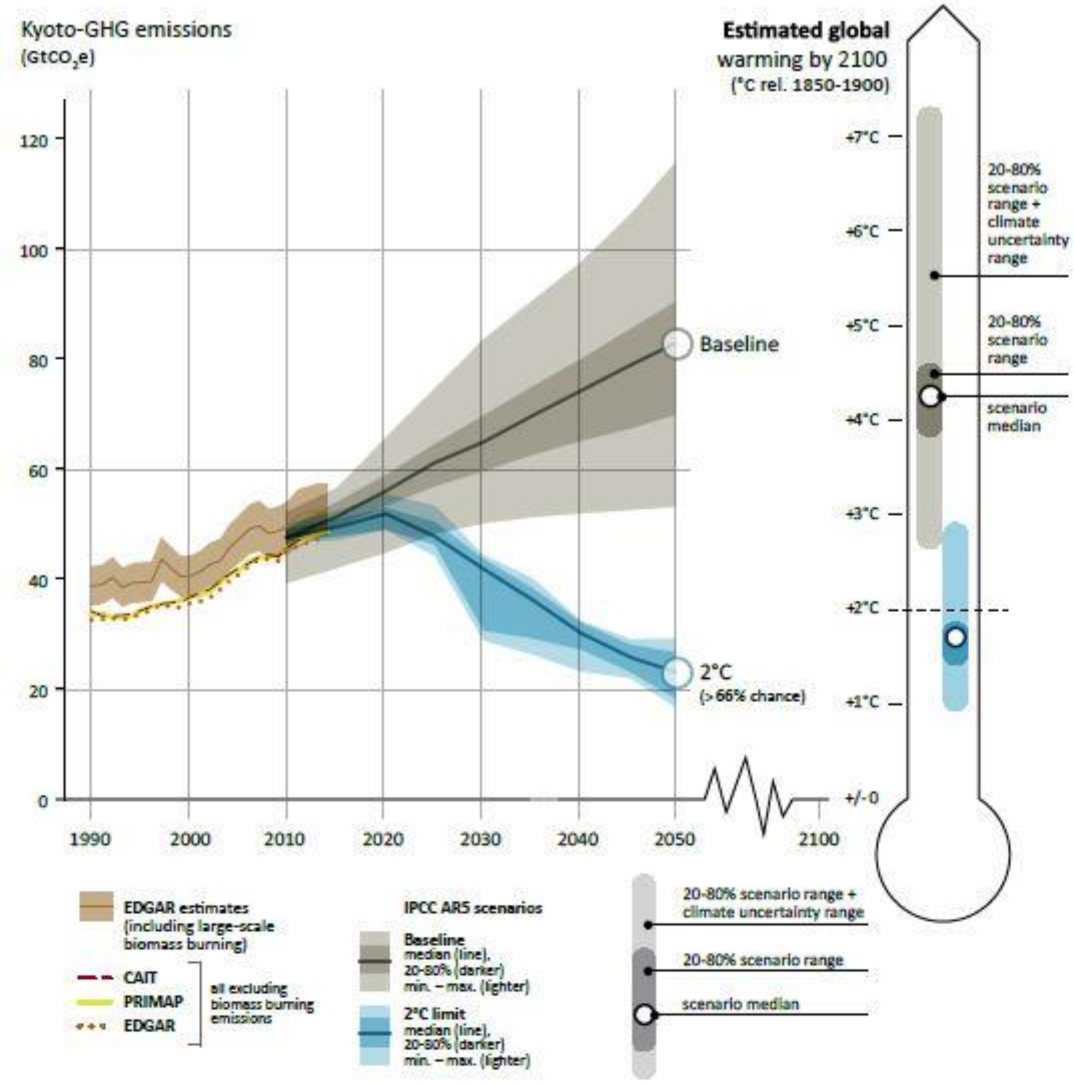

Figure 2-3 – Historical GHG emissions and projections until 2050.

Source: Olhoff et al. (2015).

Finally, it is important to highlight that the Paris Agreement is not prescriptive, which means that it does not establish a specific market mechanism to enforce climate change mitigation, giving freedom to the Parties to decide how each of them will accomplish their targets. However, it adopts the expression “internationally transferred mitigation outcomes” (ITMO) which indicates a terminology for carbon currency, giving governments a signal that a future mechanism for ITMOs should be design to deliver an ‘overall mitigation impact’ (New Climate Institute 2015).

2.2 Main Policy Instruments Related to Low Carbon Policies

This section details and discusses the policy instruments that may be adopted in the context of climate change mitigation strategies. Main focus is given to the discussion of market mechanisms for low carbon policies, such as carbon taxes and cap-and-trade systems. However, it is important to note that these mechanisms may not be implemented alone and usually they are combined to other energy policy instruments enacted to foster specific new technologies, such as feed-in tariffs or subsidies. Moreover, these instruments are elements that may influence discount rates when evaluating low carbon projects, since they deal with market failures, risk perception and access to capital. Thus, they should be considered as elements when discussing discount rate choice and evaluating how it impacts the energy system. Henceforth, in the last part of this section these instruments are also discussed.

2.2.1 Market Mechanisms for Low Carbon Policies

As stated by Kolstad and Toman (2001), climate policy design has focused mainly on the application of incentive-based instruments for GHG abatement, such as charges for carbon emissions, tradable permit or credit systems or hybrid policies. These policies generate flexible means to reduce carbon emissions at lower costs, thus, reducing the market failure of climate damage not being accounted in prices of goods and services (Morris and Mathur 2014). The same authors (Kolsad and Tomam 2001) mention some responses to incentive-based policies, like: switching to less carbon intensive fuels; adopting more energy-efficient technologies; reducing carbon content and cost of goods; increasing reforestation in order to mitigate carbon emissions and; incentivizing innovation through diffusion of cost-reduction of low carbon technologies.

Low carbon policies may imply in a series of regulatory approaches, like technology mandates (command and control approach), performance standards and emissions pricing. Goulder and Schein (2006) point that there is a main theoretical attraction of emissions pricing, which includes carbon taxes and cap-and-trade systems: the possibility of reaching emissions reductions at lower costs than under direct regulation, like mandates and standards. Still, there is much debate on what is the better option between these two.

A carbon tax is the simplest form of market-based policy. It sets a price on each unit of pollution, providing an incentive for an agent to reduce its amount of pollution, which is, in the context of this discussion, GHG emissions. Carbon taxes can be effective either based on the quantity of emissions an entity produces or based on the taxation of carbon-intensive goods and services (like gasoline, for example) (C2ES 2016a).

In fact, taxing carbon is done most indirectly, by taxing fossil fuels according to their carbon content (Kolsad and Toman 2001). Authors mention that it could be collected in several ways, like a severance tax on domestic fossil fuels and on fossil fuels imports or on primary energy inputs at transformation and transportation centers such as oil refineries and coal shippers. It is considered better to tax on the upstream in order to avoid carbon leakage and because "end-of-pipe" taxing would have to consider numerous and heterogeneous units, compromising cost-effectiveness. (Kolsad and Toman 2001; Goulder and Schein 2006).

Currently, some counties adopted carbon tax policies, like Japan and Mexico. South Africa also proposed a carbon tax scheme to reduce GHG emissions that should come into force in mid-2016 (C2ES 2016b).

A cap-and-trade system, on the other hand, is based on a limit on the emissions, not on the price of the pollutant. Once a limit on emissions is posed, costs of achieving the goal are minimized by the creation of a carbon market. In that case, a price to carbon is created indirectly by the market (C2ES 2016c). Kolstad and Toman (2001) affirm that trading carbon is somewhat more complicated than taxing and that it would also be better to distribute permits among upstream sectors for similar reasons of upstream carbon tax (compromising cost-effectiveness).

Under a cap-and-trade system, permits may be distributed freely among agents or they may be auctioned to the highest bidder. Kolstad and Toman (2001) say that efficiency increases with auctioning because it allows revenues to be used to offset distortionary taxes. Parry et al. (1999) estimate that a nonrevenue-raising carbon-trading policy could increase the net social cost of compliance, Goulder and Pizer (2006) discuss that trading program with freely distributed permits have achieved more popularity. Indeed, choosing between auctioning and the free distribution is a trade-off between distribution issues and regulatory burden, since in the free-allocation case firms bear a smaller share of regulatory burden although an auctioning system is more cost-effective[7] (Goulder and Pizer 2006).

The world's largest cap-and-trade system adopted is the European Trading Scheme (ETS), which is the key tool to reduce industrial GHG emissions in Europe. In the ETS, a cap of emissions is established and freely distributes among factories, power plants and other industrial installations and it is updated from time to time in order to make total emissions of the system fall (EC 2016b).

Moreover, companies receive tradable emission allowances and they may also buy limited amounts of international credits from emission reduction projects worldwide. Allowances are also tradable through time, since it is possible to spare allowances to cover future needs as alternative to sell them to a company short in allowances. This flexibility ensures that emissions are cut where it costs less. It is expected that sectors covered by ETS will emit in 2020 21% less than 2005 emission levels. By 2030, it is expected emissions to be 43% lower (EC 2016b). Wittneben (2009) discussed the impact of ETS in terms of emission reductions and cost to the public. She states that the massive carbon market that was constructed under Kyoto Protocol and the EU ETS has cost a lot, but it has not reduced emissions accordingly.

The same author (Wittneben 2009) discusses the main differences between carbon taxes and cap-and-trade, which is useful to the discussion of this section. First, she points that carbon prices are negotiated at national level and its level depends on the national political context. In this case, there is no limit to emission. In the case of cap on emissions, she points that the limit on emissions indicated that there will be no mitigation at higher levels that the established and that these limits are set through political bargaining across parties. She also sets the fact that both carbon tax and cap-and-trade (with auction of allowances) generate revenues to the government as a similarity of these mechanisms. However, carbon tax

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[7] Goulder and Pizer (2006) explain that an auctioning system tends to be more cost-effective because when allowances are auctioned, firms do not capture rents associated with high output prices resulting from costs of carbon emissions, avoiding firms to enjoy higher profits.

generates continuous revenue flows, although amounts are uncertain because industry tends to adjust through mitigation, meanwhile cap-and-trade has more certainty about allocated amounts, but uncertainty regarding prices.

Moreover, Wittneben (2009) shows that carbon taxes may cost less to the public sector, since it can be administered by existing institutions that already deal with tax schemes. On the opposite, a comprehensive system to administrate cap-and-trade is difficult to design, since it is necessary to deal with accounts of multiple participants, calculate and verify emission allocations and a compliance mechanism should be put in place. This is also pointed out by Ptak (2013). Another point is that carbon taxes reward emission reductions at an equal rate no matter how much the reduction costs, as cap-and-trade systems add uncertainty to the process due to price volatility. There is also the issue of rents generation: as cap-and-trade system generates rents to participants, it is not clear how it is directed and where it is applied, i.e., the possibility of this contributing to increase emissions exists. On the other hand, in the case of carbon taxes, revenues would be generated for the government and this could be directed to green projects, maximizing emission reduction.

Goulder and Schein (2006) discuss advantages and disadvantages of both market-based systems. The authors conclude that, in fact, there is no preferred mechanism to be adopted, since both approaches have equivalent potentials in different dimensions (like burden distribution between emitters, international competitiveness preservation and problems associated with emission offsets) if properly designed[8]. However, they highlight that exogenously specified price policies have attractiveness over non-specified price policies, like the prevention of emission price volatility and the minimization of expected errors in the face of uncertainties. Besides, exogenous prices are better to avoid interactions with other climate policies and they also avoid wealth transfer across borders. In that sense, the authors suggest a hybrid policy as an alternative to the separate market-based mechanisms: a cap-and-trade system with a price floor and/or a price ceiling would enjoy the qualities of both approaches.

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[8] Authors highlight that potentials will depend deeply on adequate policy design.

Goulder and Pizer (2006) also discuss price taxes versus tradable allowances in the presence of uncertainty. They affirm that although expected welfare losses are smaller in price-based instruments than in quantity-based instruments, environmental advocates prefer to keep price uncertain by adopting a cap-and trade system than to keep level of emissions uncertain by adopting a fixed carbon tax. This would enhance the guarantee that an emission limit would be respected.

Green et al. (2007) advocate on behalf of carbon taxes. They point out that the possibility of high volatility of prices under a cap-and-trade system is a disadvantage of this mechanism, since it threatens the viability of low carbon investments due to high perception of risk. Also, the adequate allocation of emissions permits is considered to be complicated by the authors, since it usually involves some arbitrary discretion. Moreover, the allowances and accounting systems tend to be very complex since agents at different points of a supply chain may claim for credits related to the same amount abated[9], which leads to double-counting. In order to solve that problem, an arbitrary manner to split these credits should be established, but it could lead to economic distortions in the market place.

On the other hand, Green et al. (2007) affirm that a revenue-neutral carbon tax should be preferred over an emissions trading scheme due to a series of reasons. Among them, they cite that it would be more effective and efficient, since it would lead to the right balance between mitigation costs and global warming reduction benefits, as the carbon tax equals to the damage per ton of CO_2. A carbon tax would also increase the costs along the energy supply chain, stimulating consumers to reduce their consumption either by reducing their use or using it more efficiently. In fact, the authors affirm that a carbon tax could create a profit niche for environmental entrepreneurs to deliver low-carbon energy at competitive prices. Moreover, Green et al. (2007) mention that a tax proportional to the fuel’s carbon content and levied at the point of first sale should be less susceptible to corruption, it enables the elimination of superfluous regulation and it would also solve the problem of price volatility (which is critical in the trading scheme). Besides, carbon taxes have the advantage of keeping

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[9] Green et al. (2007) cites as example that, as forest products industry might claim for credits for creating carbon sinks in the its harvests, the manufacturing sector the uses these wood products might claim for the same credits for sequestering carbon.

tax payments within individual countries and they provide the possibility of using its revenues to reduce other taxes on productivity, mitigating possible economic damage accrued from the raise of energy prices and leading to efficiency gains in the economy.

Ptak (2013) summarizes the main distinctions between carbon taxes and cap-and-trade systems in a table (Table 2-1). As many authors tend to affirm that carbon taxes are more efficient and straightforward than a cap-and-trade system (Wittneben 2009; Green et al. 2007; Ptak 2013), it is important, however, to bear in mind the importance of policy design when choosing between these two mechanisms, as pointed by Goulder & Schein (2013).

Table 2-1 – Carbon taxes vs. Cap and Trade Schemes.

CO_2 Tax	**Cap and Trade System**
Price (the tax rate) is known. The energya prices are predictable.	Price (of permits) is uncertain. Prices are set by markets. Price instability makes it difficult to plan abatement measures.
Taxes do not assure there will be the desired reductions of CO_2 emissions. In order to achieve the desired reductions the government has to estimate the price elasticities of demand for fuels (and inter-fuel elasticities). However, tax rates can be changed gradually (adjusted) according to the observed emission reduction.	Certainty about the quantity of emissions. The overall level of emissions is determined in advance.
It is possible to use existing administrative structures (tax collection mechanisms, enforcement).	Complex systems (for compliance reporting, monitoring) must be established.
Taxes can be implemented more quickly and easily.	The comprehensive systems are difficult to design. Issues that require consideration include inter alia: the number of tradable permits, allocation of permits (for free or by auction) or offsets for carbon sequestration projects. Cap and trade are less transparent and it may be easier to enact hidden exemptions for given sectors.
Taxes can provide substantial revenues. Recycling of revenues by lowering or eliminating distortionary taxes can increase the overall efficiency of the tax systems.	When emission permits are auctioned by the government, then these can also become a source of fiscal revenue.
Opposition to taxes by industry. Carbon tax approach (without any redistribution of tax revenues) is generally more costly to polluters than marketable permit approaches with grandfathered (distributed for free) emission permits. The reason taxes impose higher costs is that, in addition to abatement costs, polluters still have to pay the tax on their residual pollution.	Grandfathered tradable permits are preferred by industry.

Source: Ptak (2013).

2.2.2 Energy Policy Instruments

Besides the main market mechanisms for low carbon policies presented in the previous chapter, there is also a set of other instruments that may be adopted in a context of low carbon policy or may be combined to it with distinct objectives, such as technology diffusion and energy efficiency. It is important to bear these instruments in mind as they may be broadly adopted to eliminate barriers to implementation of mitigation options, constituting supporting mechanisms towards a low carbon pathway. Moreover, as the purpose of this thesis is to identify the impact of discount rates on Brazil’s energy systems, it is important to expose policy instruments that might influence discount rate choice when evaluating energy projects, which bridges the discussion of policy-making with the discussion of discount rate choice, to be held in the next chapter.

IEA (2015) proposes a classification of policies and instruments (Figure 2-4) that could foster technology diffusion, including mitigation technologies, that is mainly based in the type of policy, i.e., the main characteristic of the adopted policy instrument:

- Information and education: this category includes measures to improve knowledge level and capacitation regarding low carbon options. In fact, an important part of barriers to implementation are related to transaction costs associated to the capacity of agents and information asymmetries. Moreover, products and processes certification instruments are also classified under this category.
- Economic instruments: these are instruments and measures that stimulate some activities, modify behavior of economic agents through price signals, fiscal incentives or financing. They also seek to deal with different opportunity costs of capital incurring from different conditions of access to capital (also associated with the spread of economic agents). These instruments include direct financing and the market mechanisms discussed in section 2.2.1.
- Institutional arrangement: this is related to the establishment of an institutional framework able to orientate and support the implementation of technological options and/or mitigation options. It includes development agencies, sectorial plans, regulatory organs, etc.
- Research Development and Demonstration (RD&D): this category includes the support to the technological development of either disruptive innovative options or options needing demonstration and technological learning. It considers direct investment, fiscal incentives, market niche creation through government purchases, etc.
- Regulatory instruments: these include targets, obligations and standards. They relate to command and control instruments aiming at defining standards or targets of

emissions or performance in terms of product or process. Minimum standards of energy efficiency, maximum emission targets, definition of minimum values of participation of specific technologies options in the technology portfolio of firms, these all relies in this category, for instance. It also includes the obligation of maintaining and updated emission inventories.

- Voluntary agreements: these measures are voluntarily adopted either by public organs or by private agents, either in a unilateral or negotiated way. In the first case, it is related to anticipating technological changes or generating value to stakeholders (image value, for instance). In the second case, it is related to sticking to proposals of voluntary agreement for specific targets (such as productivity gains, emissions intensity reductions, etc) made by public agents.

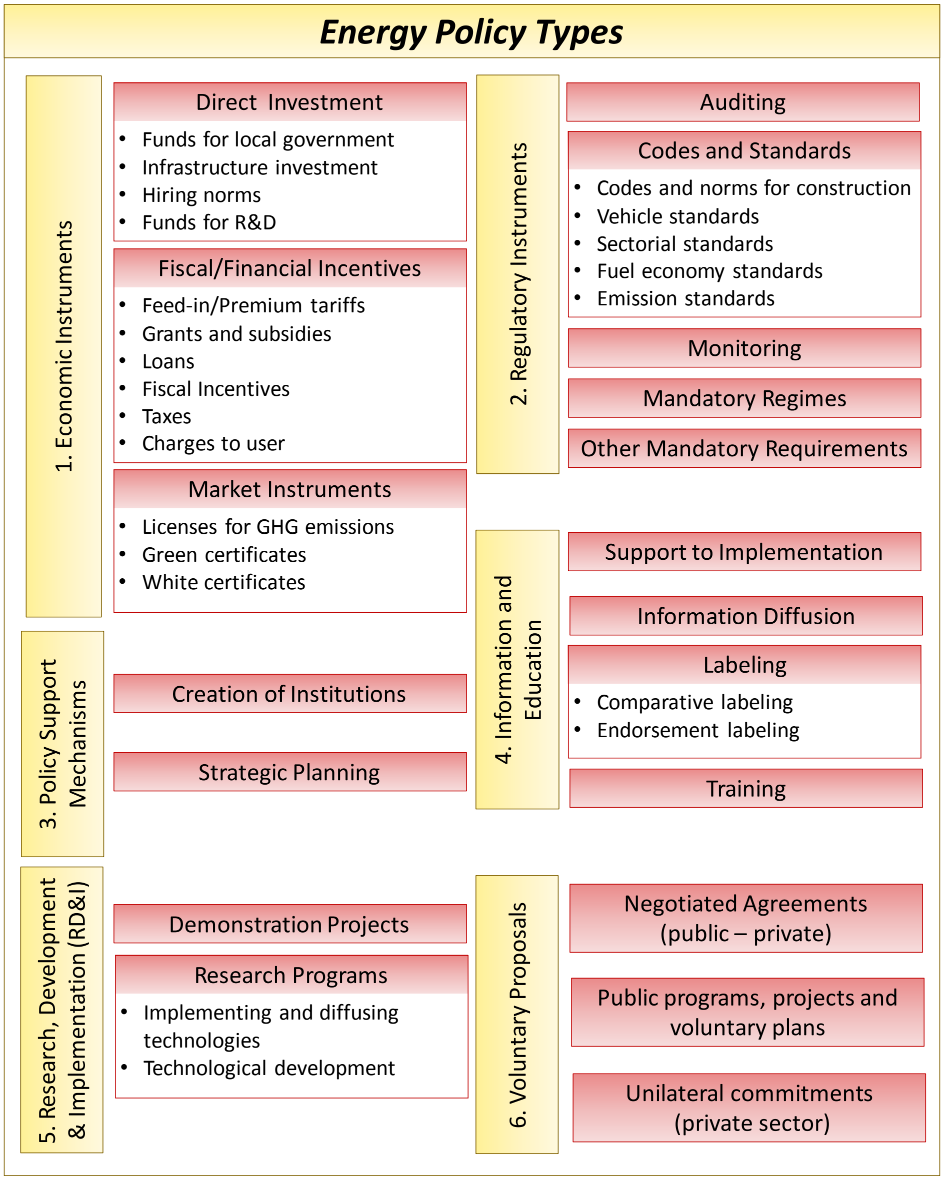

Figure 2-4 – Energy policy types.

Source: Adapted from IEA/IRENA (2011).

It is important to note that the main target of the policy may vary, but, still, a specific policy with a specific focus might entail co-benefits related to other issues. For instance, greenhouse gas abatement policies might incur in energy cost reduction due to energy efficiency gains and the opposite also might happen. Another example is when establishing renewable energy minimum adoption in an energy system, since the mitigation co-benefit is also presented. This is the main reason why energy policy instruments might serve (intentionally or not) as supporting mechanisms to low carbon policies.

Moreover, given the design and co-benefits generated by specific policies that might be combined with climate change mechanisms, it is expected that these policies change the perception of attractiveness of technologies by investors. This happens by the attempt to eliminate market barriers, reduce the perception of risks and provide access to capital, as it will be discussed in the next chapter. It should be noted, then, that these instruments have direct effect on discount rate to be chosen when evaluating projects, as it measures the opportunity cost of capital of one project and these instruments may turn them more competitive. This gives some perspective on the set of scenarios adopted in this thesis, as they combine climate policies with different types of discount rates, as it will be better detailed in chapter 4 (methodology chapter). In fact, scenarios reflected in this thesis might suggest that one or more instruments are combined with low carbon policy in different extents. A R&D promotion policy, for instance, could improve learning of technologies, reducing risks and costs, and this would be reflected in discount rates. Similarly, the improvement of financing conditions with the established of specific discount rates could also play a whole in the viability process of low carbon technologies, justifying the consideration of different discount rates (with and without financing option) when assessing the mitigation option.

2.3 Current Status in Brazil

Brazil is in a strong position in the climate debate (Schaeffer et al. 2015). This is because it is engaged in negotiations about climate change mitigation agreements as it enjoys a favorable position regarding its energy sector. Its energy matrix has a high share of renewables when compared to the world, as can be seen in Figure 2-5. In 2012, more than 40% of domestic energy supply in Brazil came from renewables, including biofuels, biomass, hydroelectricity, wind and solar. Meanwhile, Global figures show that renewable energy supply worldwide is less than 15% of the total.

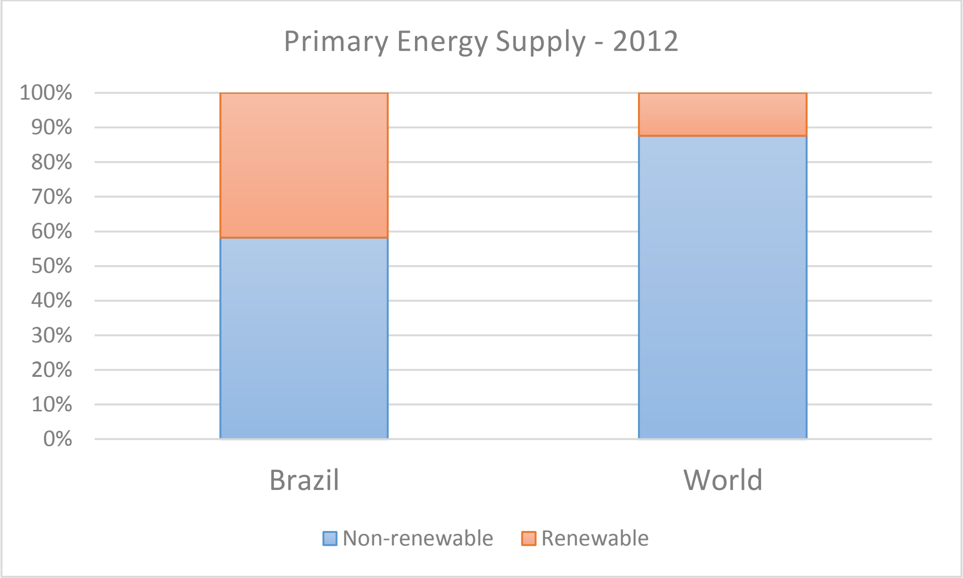

Figure 2-5 – Renewable and non-renewable shares of primary energy supply in 2012: Brazil vs. World.

Source: Own elaboration based on EPE (2015a).

More recent figures depict domestic energy supply in Brazil per source in 2014 (Figure 2-6). As it is possible to observe a significant role of hydraulic energy and sugarcane products, the sum of renewable sources shows that renewable share in 2014 was a bit less than 40%. This brings an important fact regarding energy sector in Brazil: as a developing country, Brazil has been experiencing economic growth in the last few years, which is leading to an increased energy demand. As the need to expand the energy system to meet this demand grows, Brazil's reminiscent hydropower potential is under environmental constraints, since it is located in Amazonia (Schaeffer et al. 2015; Lucena 2010; Lucena et al. 2010). Also, pre-salt[10] oil reserves are being exploited and there are prospects of deploying low-cost coal-fired electricity generation (EPE 2015b, Schaeffer et al. 2015). These elements bring doubt about keeping Brazil's energy matrix clean with high levels of renewables under such conditions.

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[10] Pre-salt oil reserves are located under a salt layer in deep water locations.

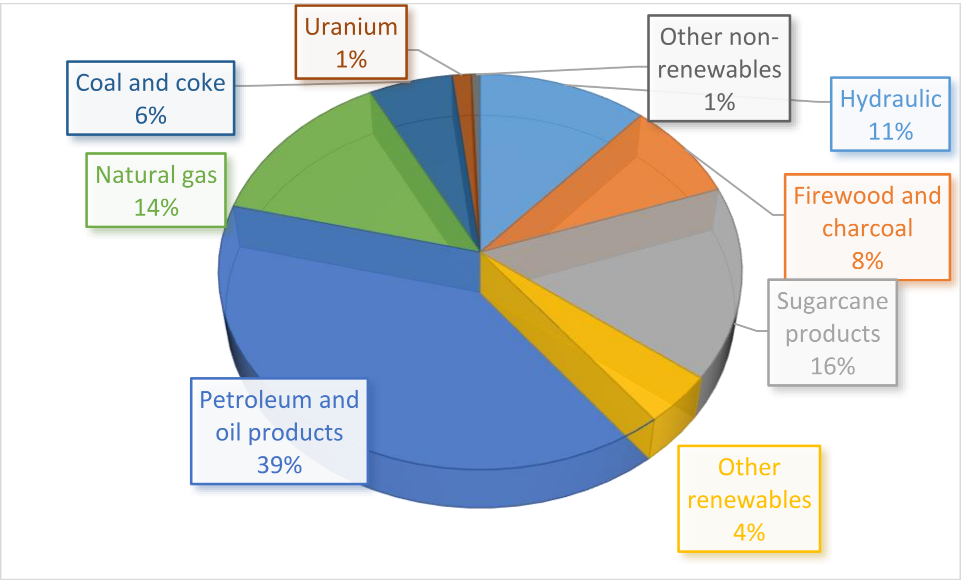

Figure 2-6 – Domestic energy supply (%) per source in Brazil – 2014.

Source: EPE (2015a).

In fact, Brazil's energy sector has gained share in CO_2 emissions in the last years and this is not only because of the increase in its carbon-intensity, but also because of emission reduction efforts in land use sector, as may be observed in Figure 2-7. Figure 2-8 shows emissions in CO_2-equivalent and it can be observed that energy sector is the third responsible for CO_2-equivalent emissions in Brazil, being behind land-use change and agriculture (MCTI 2015a).

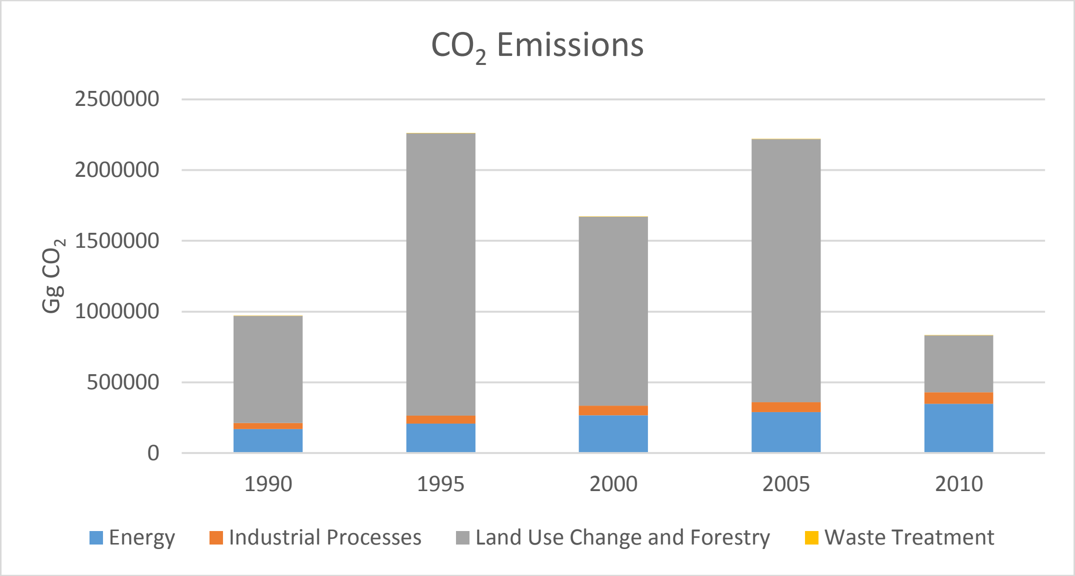

Figure 2-7 – Net CO$_2$ emissions evolution per sector.

Source: Own elaboration based on MCTI (2015a).

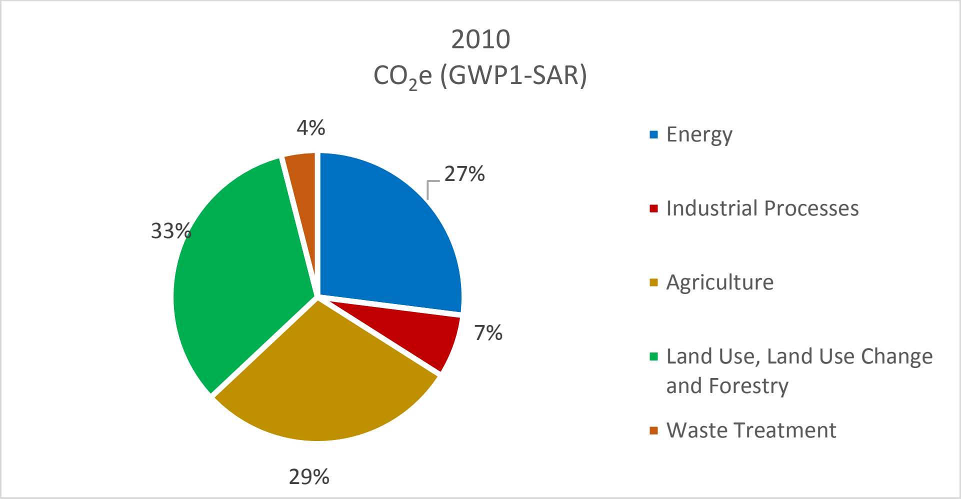

Figure 2-8 – CO$_2$-equivalent emissions per sector in 2010[11].

Source: MCTI (2015a).

Therefore, Schaeffer et al. (2015) affirm that Brazil is at a crossroads regarding its energy future and sustainable development due to a combination of supply-side and demand-side factors that might increase its carbon intensity. Currently, Brazil is under an economic and

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[11] Based on metrics of IPCC's Second Assessment Report (IPCC 1995).

political crisis that is leading to a recession period, with estimates of a -3.5% retraction in the economy in 2016, as projected by IMF (2016) and this might relief the pressure on energy supply in the short-term. Notwithstanding, since Brazil is still in a developing country position, in order to avoid an increase in carbon-intensity of its energy system, it will have to make a political effort to maintain carbon emissions relatively low.

Currently, climate policy in Brazil is mainly influenced by land use, land use change and forestry because of deforestation and degradation in the Amazon region (Schaeffer et al. 2015). Schaeffer et al. (2015) describe and explain institutions in Brazil somewhat linked with climate change policies, such as: the Ministry of Science Technology and Innovation (MCTI), which is responsible for the coordination and implementation of agreements under UNFCCC; the Inter-ministerial Commission on Global Climate Change (CIMGC), established to articulate government actions resulting from UNFCCC; and the Inter-ministerial Committee on Climate Change, issued to direct the elaboration, implementation, monitoring, evaluation and proposals for the periodic review of the National Plan on Climate Change (NPCC). The authors mention that Environment Ministry (MMA) and Mines and Energy Ministry (MME) also take part on climate change issues.

Policy wise, the National Policy on Climate Change (MMA 2008) was the first low carbon policy ever implemented in Brazil, although it did not have a mandatory character towards UNFCCC. The goal established by the policy was announced as voluntary mitigation targets at 2009 Conference of the Parties: an emission reduction of 36.1% to 38.9% by 2020 in relation to business-as-usual levels. However, Schaeffer et al. (2015) discuss that, for the energy sector, NPCC plan did not contemplate a low carbon scenario, since it was based in a reference scenario outlined by the Ten-Year National Energy Expansion Plan (EPE 2015b) and, thus, did not constitute a big effort towards a low carbon energy system.

Schaeffer et al. (2015), based on MMA (2008) list policy's main objectives: '(i) stimulate increased efficiency in a constant search for better practices in the economic sectors; (ii) keep the high share of renewable energy in the power mix, preserving the important position Brazil has held in the international scenario; (iii) encourage the sustainable increase in the share of biofuels in the national transport mix and also work towards the structuring of an international market for sustainable biofuels; (iv) seek for a sustained reduction in deforestation rates in all Brazilian biomass, in order to reach zero illegal deforestation; (v) eliminate the net loss of forest coverage in Brazil by 2015; (vi) strengthen inter-sector actions concerned with the reduction of the vulnerabilities of populations; and (vii) identify environmental impacts resulting from climate change and stimulate scientific research that can outline a strategy to minimize the socioeconomic costs of the country's adaptation.'

The next step for the climate change policy in Brazil is mitigation commitments post-2020, as a continuation and enhancement of Kyoto's Protocol. These commitments are based on Brazil's position assumed at COP21, in Paris, which is under INDC announced by the president before the Conference.

Current Brazil's intended nationally determined contribution (INDC) as accepted and reported in Paris agreement assumes absolute emission targets of 1.3 $GtCO_2e$ by 2025 and 1.2 $GtCO_2e$[12] by 2030, which correspond to reductions of 37% and 43%, respectively, compared to 2005. Corresponding per capita emission in these periods should be 6.2 $GtCO_2e$ and 5.4 $GtCO_2e$. Percentage reductions are related to reported emissions of 2.1 $GtCO_2e$ in 2005[13] (MCTI 2015b).

The Brazilian INDC as approved for the Paris Agreement has also sectorial goals for land use and forestry, energy and agriculture. Figure 2-9 summarizes measures included in the INDC for each sector. In the energy sector, there are ambitious goals of increasing non-hydro renewable sources in primary energy matrix and in the electric matrix.

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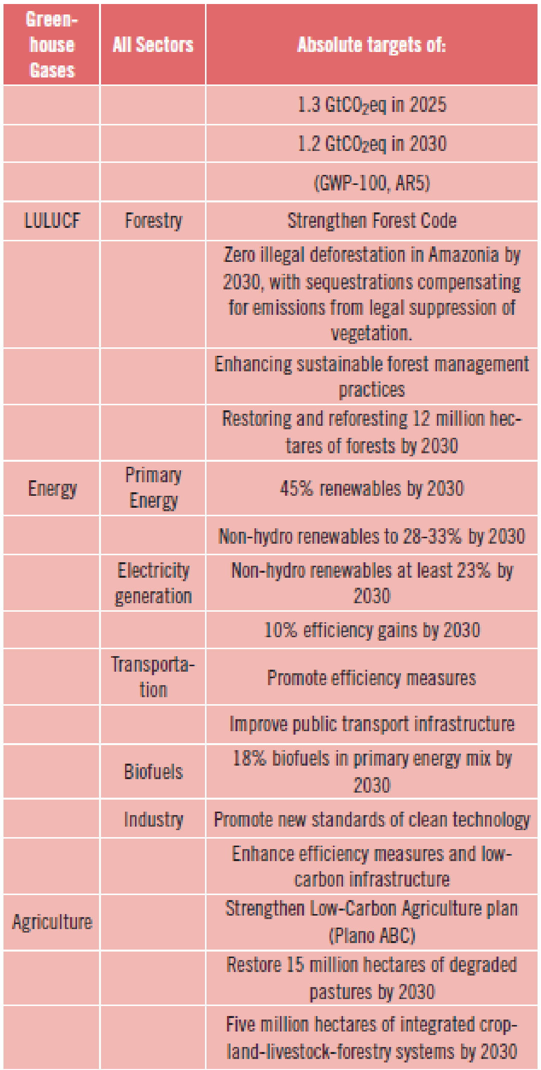
[12] GWP-100, AR5 metric.

[13] Spencer et al. (2015) bring the debate about 2005 reported emissions, since there are discrepancies in reported emissions in different documents. The Second National Communication (MCTI, 2010) reported 2.29 $GtCO_2e$ in 2005, while the Third National Communication (MCTI, 2015a) reports an emission level of 2.74 $GtCO_2e$. The closest estimation of 2005 emissions is 2.04 $GtCO_2e$ reported in the 2014 report of annual emissions estimates published by the Ministry of Science, Technology and Innovation (MCTI, 2014). These estimates do not constitute an official report to the UNFCCC, though (Spencer et al. 2015).



Greenhouse Gases	All Sectors	Absolute targets of:
		1.3 $GtCO_2eq$ in 2025
		1.2 $GtCO_2eq$ in 2030
		(GWP-100, AR5)
LULUCF	Forestry	Strengthen Forest Code
		Zero illegal deforestation in Amazonia by 2030, with sequestrations compensating for emissions from legal suppression of vegetation.
		Enhancing sustainable forest management practices
		Restoring and reforesting 12 million hectares of forests by 2030
Energy	Primary Energy	45% renewables by 2030
		Non-hydro renewables to 28-33% by 2030
	Electricity generation	Non-hydro renewables at least 23% by 2030
		10% efficiency gains by 2030
	Transportation	Promote efficiency measures
		Improve public transport infrastructure
	Biofuels	18% biofuels in primary energy mix by 2030
	Industry	Promote new standards of clean technology
		Enhance efficiency measures and low-carbon infrastructure
Agriculture		Strengthen Low-Carbon Agriculture plan (Plano ABC)
		Restore 15 million hectares of degraded pastures by 2030
		Five million hectares of integrated cropland-livestock-forestry systems by 2030

Figure 2-9 – Summary of measures included in Brazilian INDC.

Source: Spencer et al. (2015) based on MCTI (2015b).

The Brazilian INDC has suffered critics by specialists similar to the ones suffered by Paris Agreement as a whole: that targets are not ambitious enough to reach the goal of keeping temperature rise below 2°C plus they ‘fall short from what the country needs’[14] (CEBDS 2015). Although it was considered ambitious because it was the only absolute reduction target presented by a developing country, reforestation targets were criticized for not being compatible with Brazilian Forest Code and total renewable energy share were also

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[14] This have been published in the press. BBC website (BBC 2015) and WRI website (WRI 2015) may be cited as examples.

criticized for not differing a lot from current share because of hydropower (CEBDS 2015). It is important to highlight, as discussed before, that INDCs should be updated every five years under the Paris Agreement, which could lead to more stringent targets in the future.

Therefore, it may be inferred from the discussion that although in the last few years Brazil's commitment with climate change was not seen as a priority (Schaeffer et al. 2015), now it is hitting the spotlight with Brazil assuming a strong position in global negotiations. Although it was not established how the country's reduction targets will be achieved, this attitude towards climate change debate will probably lead to promotion of programs aiming at incentivizing emission reductions in important economic sectors, including the energy sector. The impact of these possible programs and policies shall be well evaluated in order to guide policymakers on the best pathway to follow. Moreover, the fact that mechanisms and instruments to foster a low carbon energy system in Brazil are not defined highlight the importance of considering different sets of low carbon scenarios when assessing possibilities through energy systems modeling.

Technology wise, Brazil's position is not clear as to what are the specific technologies that should help address the emission reduction targets, such as renewable technologies and carbon capture and storage. When evaluating such technologies and policies, the right economical and financial parameters, such as discount rate, should be chosen in order to establish access to capital and time preference. This will be focus of the next chapter.

3 Discount Rate Choice and Other Temporal Issues in the Climate Change Policy Context

Discounting is commonly used to model behavior and to evaluate costs and benefits that accrue over different time periods, according to Pollitt & Billington (2015). Indeed, a discount rate puts a weight in short-term balance relative to long-term balance, resulting in a perception of cost-effectiveness and financial viability of policy options under a determined period. The discount rate is the interest rate used to discount future cash flows and bring them to present value and indicates one's valuation of his/her future benefits from current investment (Chunekar & Rathi 2012). Naturally, within discount rate rationale relies the issue of time value of money, that regards the idea that money available today is worth more than the same amount in the future because money can earn interest according to the defined rate of return.

The first attempt to deal with decisions involving trade-offs occurring at different times was made in 1937 with the proposition of the discounted utility model by Paul Samuelson (Samuelson 1937). A central premise of the model was that all motives underlying intertemporal choice can be condensed into a single parameter, the discount rate. However, the work of Frederick et al. (2002) shows that there is great disagreement in measuring time preference by one unique indicator. This, as point the authors, may reflect the difficulty in isolating time preference and ignoring other considerations such as intertemporal arbitrage, uncertainty about future reward or penalty, inflation (when nominal monetary amounts are used), expectations of changing utility and considerations of habit formation.

According to Harrison (2010), how people value costs and benefits spread through time are revealed through the trades they make in the capital market and the discount/interest rate is the price people pay to have resources now rather than later. Pratt and Grabowski (2010) defines discount rates as the sum of any or all of four components: risk-free rate, general equity risk premium, size factor and, specific company and/or industry risk adjustment factor.

Discount rate choice is of great importance to policy analysis since it allows evaluating the opportunity cost of each policy, accounting for the time-value of expenditures and revenues. The evaluation of investments in the energy sector and in low carbon options proves to be of especial relevance in that context, since there is a considerable variation in different energy technologies' cost structures, which means that some projects have high upfront costs with low operational costs along their lifetime (like renewable energy projects) while other projects have low initial capital costs and high operational and fuel cost (like conventional fossil-fuel based thermal power plants). In that sense, depending on the choice of the discount rate to be adopted, some technology projects can be put in disadvantage in relation to conventional projects because future cost savings may be discounted and put less weight. In short, variations in the discount rate affects not only the cost of policies, but also the choice of technologies in an optimal cost scenario (Pollitt & Billington 2015).

The issue of intertemporal discounting of technology options with heterogeneous characteristics is intrinsically linked to climate change policy evaluation, because the main target of this type of policy is to make viable low carbon technologies by eliminating barriers and promoting reduction costs, which is linked to the discount rate adopted. Also, climate change debate brings to light the discussion about the intergenerational issue and the need for attributing a higher value to benefits obtained in the long term in order to make it viable mitigation actions today that will take time to bring benefits. Hence, it is paramount to bear in mind the role of discount rates in evaluating public policy and how they may affect decision-making. The approach chosen when evaluating long-term issues, such as climate efforts, can have a significant impact on results and on the policy choice in the present to influence the future.

In fact, commonly there are two main approaches for defining discount rates: the descriptivism and the prescriptivism. Defining these approaches is important as both are opposite positions when choosing discount rates and choosing a descriptivist or a prescriptivist rate when evaluating climate change costs has been under debate as the choice may bring different results, as exposed in Nordhaus critics to Stern (which will be discussed in the following sections). The descriptivist approach of choosing parameters when estimating discount rates considers that parameters should reflect as much as possible how society discounts, in accordance with Arrow et al. (1996)'s affirmation that "the appropriate social welfare function to use for intertemporal choices is revealed by society's actual choices". The prescriptive approach of choosing parameters is based on ethics from specialists responsible for the social planning regardless of market rates and real society perspective towards future generations. The main criticism descriptivists have in relation to prescriptivists is that their point of view is elitist, since their point of view is imposed to society. However, Baum (2009) points out that even under a descriptivist approach, value judgements are unavoidable when evaluating market discount rates since decisions regarding standing, defining who makes the society, measurement, how to assess society's point of view, and aggregation, how to combine individual's points of view, are necessary.

Moreover, the intertemporal choice might not only be linked to discount rate when it comes to climate change mitigation. The context of technological systems and their interactions might foster or might difficult, delaying or not, investments in innovation. Besides, the global context of mitigation might lead to different configurations of policy engagement: as there are different levels of development across countries, different responsibilities related to past emissions and different perspectives of future GHG emission figures for each country. These discrepancies might result in different levels of commitments and different timing of national and regional-level policies for different countries. These elements regarding time preference should also be explored, as they have direct impact on climate change mitigation consequences.

Therefore, bearing in mind the main goal of this thesis, in this section the different attributes and interpretations of discount rate will be discussed in order to make it clear to the reader the different approaches for selecting the discount rate. First, its role as an opportunity cost of capital indicator under a market perspective will be exposed, as well as its relation with risk and with market barriers. Then, the climate change debate will be brought into light and the role of discount rates as a social welfare indicator for environmental projects evaluation will be exposed. Moreover, the last item of this chapter explores other elements related to time preference that once combined with distinct discount rates, might have a significant impact on the low carbon transition.

3.1 Discount Rate as the Opportunity Cost of Capital

In this section it will be discussed the discount rate characteristics as the opportunity cost of capital, i.e., as a parameter to indicate access to capital, perception of risks and of market failures. Under this context, commonly two approaches are adopted in cost-benefit analysis, usually depending on the perspective of the analyst, which may lead to market discount rates (desciptivist) or social discount rates (prescriptivist). Both approaches will be discussed next.

3.1.1 The Market Approach

Discount rates should reflect the rate of return and the capital cost of investments, and its adequate choice is of great importance to the evaluation of costs and long-term benefits of different policy scenarios (Steinbach et al. 2015). Hence, economic assessment is highly influenced by discount rates since it constitutes the harmonization of present and future values requiring a level of discounting of payments and income streams (Steinbach et al. 2015). This market oriented approach to the discount rate selection follows a descriptive point of view, according to which discount rates should be based on how people decide on the day-to-day their investments.

Damodaran (2015) defines cost of capital as “the opportunity cost of all capital invested in an enterprise”. The cost of capital includes all sources, as debt and equity and this measure is based on what you give up when deciding to spend a scarce resource for a specific purpose. Harden (2014) discusses factors that go into and how to calculate the weighted average cost of capital (WACC) of oil and gas companies, defining the simplest form of the WACC, which is the sum of each capital components’ cost multiplied by their weight, as shown in (Equation 3-1). This is one approach to estimate the discount rate.

$$WACC = {}^{E}/_{V} * Re + {}^{D}/_{V} * Rd * (1 - Tc)$$

(Equation 3-1)

Where:

Re is the cost of equity;

Rd is the cost of debt;

E is the market value of the firm's equity;

D is the market value of the firm's debt and

Tc is the corporate tax rate.

The calculation is basically made in three steps: cost of capital components; capital structure and weight of each component. Capital components are debt and equity: debt relates to the interest rate inputted to the company's debt, and equity relates to the opportunity cost of investing in a specific company, which is inferred by comparison with other investments with the same risk profile, or with the rate of return of a risk-free investment plus the return for bearing extra risk[15]. Capital structure takes into consideration the proportion of debt and equity capital based on their market values and the weights of each component should reflect how much it contributes to the capital structure (Damodaran, 2015).

A firm's WACC is the overall required return on the firm as a whole. Harden (2014) concludes that the cost of equity is the biggest driver of WACC, since the cost of debt is not so different among big and small companies. Companies should be cautious when and if adding additional risk premiums due to locational, operational or mechanical factors of the assets. The Brazil-risk, for example, adds additional risk premium to investments executed in Brazil due to barriers and market failures like high public interest-rates; high inflation and low investor confidence due to political and economic uncertainties in the long term; and

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[15] This is based on 'Capital Asset Princing Model' (CAPM). It is the most used method to calculate the cost of equity.

structural inefficiencies in the long-term (such as complex tax system, heavy tax load, low labor productivity and inadequate infra-structure), as explained by Spencer et al. (2015).

Discount rate choice, in fact, is related to the risk level of projects. Hirshleifer (1961) demonstrates that there is a positive market premium on risk, meaning that yields of risky investments will be higher than yields of sure investments. In fact, the author affirms that investors should discount risk at a rate between sure and risky prospects established by the market for the risk-class in which the project is included. Stiglitz (1989) affirms that a firm cannot divest of the risks it faces, but they can act in a more risk-averse manner and this will influence the willingness to invest and the rate of growth of productivity of the firm.

Also, the risk is correlated with the maturity level of investment, since investments with innovative configuration or technologies are not sure investments as their development pathways, technological constraints and activity costs are not well known. Therefore, a technology option taking part in a specific project will have a risk premium as high as its maturity level and probably it will have a low rate of adoption at least in first periods of diffusion, as demonstrated for gas-to-liquids (GTL) plants by Castelo Branco et al. (2010).

Indeed, there is a rate of adoption related to each innovative low carbon technology, which depends on factors like technology's relative advantage (the degree to which it is perceived as being better than other technologies), compatibility (if technology is consistent with existing values), complexity (how difficult it is to understand and adopt the technology), triability (the degree to which the technology may be experimented with in a limited basis) and observability (the degree to which results of adoption are observable) (Rogers 2003).

As the objective of the chapter is not go deep into the definition of what is each of these elements, it is important to note, however, that all of them are related to the agent's perception of risk embedded in technology's adoption. Consequently, it is intuitive to imagine that discount rate choice is intrinsically correlated with technology's diffusion and its rate of adoption. In fact, if technology is advanced in its diffusion curve and has gained scale, its consolidation lowers its uncertainty (Rogers 2003) and, hence, reduces the perception of risk leading to a choice for a lower discount rate[16].

As the perception of risk is intrinsically related with discount rate choice, it is also related to the evaluation of the true cost of capital of one investment. There are discussions in available literature about how discount rates reflects properly the true cost of capital of an investment in the energy area and how the mischoice of it can cause a gap between real use and optimal use of technologies (Jaffe and Staves 1994; Gerarden 2015; Howarth & Andersson 1993; Sorrell et al. 2011).

The energy efficiency gap, for example, is defined by the differential between the currently achieved efficiency level and the cost-effective level at prevailing prices. This gap is commonly explained by the market barriers related to consumer's decision-making (Howarth & Andersson 1993). A barrier is defined by Sorrel et al. (2000) as the mechanism that inhibits investment in energy efficient and economically efficient technologies. This may include misplaced incentives, financing (through lack of access to capital), imperfect competition leading to market power and/or mispricification through regulation.

A market barrier will exist when there is a market failure, which constitutes an element that causes markets to deviate from the perfect competition, i.e., that leads to the non-efficient allocation of resources. The violation of conditions that lead to the optimal allocation of resources (free exchange between buyers and sellers, benefit maximization and cost minimization through competition between consumers and producers, known market prices and zero transaction costs) results into four types of market failure: incomplete markets, imperfect competition, imperfect information and asymmetric information (Sorrel et al. 2000). These failures end up affecting agent's behavior or investment options available to

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[16] This is true especially for external, business and technological risks. Sorrell (2015) argues that, for energy efficiency projects, the argument that high discount rates may be a rational response to risk does not apply to all cases because of inconsistent behavioral assumptions like the ignorance of costs of delaying projects and the assumption of total information of consumers about characteristics of technologies.

them, inflating discount rate adopted by them when making investment decision (Pollitt & Billington 2015).

In fact, Jaffe and Staves (1994) point out that different views about technology-related factors leads to different views on technology use, constituting the market barriers. For example, agents' perception about uncertainty of prices in the future, about actual savings from new energy technologies and investments' irreversibility might turn discount rate choice for CBA (cost benefit analysis) much higher than the one adopted in regular calculations that takes into account only economical and technical parameters (Jaffe and Staves, 1994; Frederick et al. 2002). Gerarden (2015) points out, however, that distinguishing capital market failures from lack of underlying demand for energy-saving technologies as promoter of high discount rates might be tricky. Indeed, it is possible to estimate real implicit discount rates (and how far they are from the market rate and social rate) only when agent is seeking to minimize discounted lifecycle costs and errors regarding time horizons, agent' beliefs or inattention do not happen (Gerarden 2015).

Climate change is a real environmental issue that has been leading to a technological transition in energy systems and this transition may also be slowed down by barriers. The development of new technologies with low carbon content have been the key driver to foster sustainability. That innovation movement brings the need to promote new technologies, reduce their perception of cost and risks. In fact, Gillingham & Sweeney (2012) discuss barriers to implementing low carbon technologies, differentiating 'barriers to adoption' from 'market failures'. As the former is defined by what effectively reduces the chances of adoption of a given technology, being macroeconomic or technology-specific, the latter refers to barriers that reduce the penetration of a given technology by reducing economic efficiency, like externalities and asymmetric information. They mention the high cost of renewables and CCS technologies as a barrier to adoption that does not present a rationale for economic efficiency or improving policies, but the innovation and learning process that brings down cost have market failures that could constitute motivation for policy.

As the probability of an organization to implement one given (low carbon) technology is intrinsically inversely proportional to its private cost, i.e., it decreases as private cost increases, some policies and regulatory rules might force implementation. It can be said that this effort comes in a way to cause a decrease in discount rates adopted for technology's cost-benefit analysis, as it is related to access to capital and perception of risks. The rationale is that low carbon policies promote higher access to capital to allow investment and reduce the risk of the technology option, leading to lower discount rates. Hence, the adoption of declining discount rates when accessing low carbon policies in an integrated modeling approach might approximate the analysis to what happens in reality, when effects of learning exists and policies for technology promotion are frequently adopted to foster development. The discussion about declining discount rates will be detailed in the next section (3.2).

3.1.2 The Social Approach

When it comes to investments in energy, which are considered to be a merit good, it is important to evaluate if discount rate adopted is anywhere near social discount rate when analyzing future benefits (like energy savings or CO_2 mitigation) of public policy-making decisions (Jeffe and Stavins 1994). The social discount rate can be defined as "society's relative valuation on today's well-being versus well-being in the future" (Zhuang et al. 2007, pp. 11). The choice of the social discount rate is important because, once it set too high it might eliminate socially desirable projects and, once it is set too low it might incur in inefficient investments. In the same extent, high rates will favor projects that will bring short-term benefits, as low rates should favor projects that will bring benefits in the far future (Zhuang et al. 2007).

Zhuang et al. (2007) affirms that if the world were free of distortions, then the market and the social discount rates would be equal. However, in a world with market distortions, the market interest rate no longer reflects the marginal social opportunity cost of public funds, which refers to the social discount rate.

Pollitt & Billington (2015) say that social discount rates are used in order to reflect the relatively low cost of capital for government institutions when evaluating policies' outcomes.

Napalang & Ueda (2005) approached this issue by evaluating the gap between social optimal timing, best time to invest[17] under government's point of view, and private social timing, best time to invest under private sector's point of view. They argue that government is altruistic and considers all stakeholders, which makes social optimal timing more efficient[18]. In that sense, government should adopt policy instruments in order to persuade private sector to invest at proper timing. Once again, discount rate is impacted, as the effort to bridge the gap of timing is also the effort to bridge the gap between social and private opportunity cost.

In fact, there is not just one methodology attempting to estimate the social discount rates[19], which reflects different visions on how public investment affects domestic consumption, private investment and the cost of international borrowings. Moreover, Zhuang et al. (2007) show that social discount rates might vary significantly across countries, with developing countries adopting high level social discount rates (between 8% and 15%) and developed countries adopting low level rates (between 3% and 7%). This is a result not only of the analytical approach adopted in each country, but also of the different perceived social opportunity cost of public funds. In fact, as developing countries need social investments in a more emergency basis, they tend to prefer investing now than later, leading to higher social discount rates.

Steinbach et al. (2015) in a report discussing discount rates in energy systems bring some conclusions to the adoption of social discount rates and individual (market) discount rates when evaluating energy systems: social discount rates should be derived from a proper methodology that considers time preference and should weight intergenerational welfare. It should, in short, reflect a risk-free discount rate declining over time, when long time horizons

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[17] Best time to invest is the time at which net present value of the project is maximized (Napalang & Ueda 2005).

[18] It should be mentioned, however, that social discount rates might be high for some governments, when they focus in the short term and worry about their power maintenance (Zhuang et al. 2007).

[19] Among them, it is possible to mention the "marginal social opportunity of capital" and the "social rate of time preference". As the former is based on practical arguments of scarcity of resources and competition between social and private sectors, the latter is based on society's will to postpone a unit of current consumption in exchange for more future consumption (Zhuang et al. 2007).

are adopted[20]. Meanwhile, individual discount rates should be differentiated in accordance with types of investors, since each of them will have a different implicit perception of financial constraints, information gaps and rationality. In that sense, sensitivities are recommended to capture the influence of these parameters on overall results.

While, under a social environmental approach, the choice of discount rates impacts the investment decision for low carbon technologies, under a private perspective it also impacts the decision to invest in specific projects. These are two different approaches for discount rate choice and these can result in different investment strategies. Although the main objective of this thesis is climate change policy-related, the impact of access to capital in discount rate decision should not be dismissed, since, in general, that is the main driver for stakeholders in the energy business environment. The mitigation debate involves discussing and deciding to invest in technologies that have not reach maturity yet and the decision to invest crosses the discussion of level of risk, market failures and discount rate choice. In that context, integrating these aspects of choice is important since, in a low carbon initiative context, both social and market approaches should be considered and brought together.

Therefore, once discussed the role of discount rates in project valuation and its different interpretations and implicit premises, it is important now to introduce in more detail the intergenerational issue on discount rate and how it relates deeply with climate change policy evaluation. The idea is, once exposed both approaches to discounting, to be able to understand in theory how discount rate choice may affect climate policy decision and justify properly the methodology adopted in this thesis in order to evaluate Brazil's energy system under different sets of climate change policies.

3.2 The intergenerational Issue and Discounting on Climate Change Policy Analysis

As well pointed out by Goulder & Williams (2012), the adequate choice of a discount rate is critical for any policy assessment related to climate change mitigation, and Gollier et

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[20] Hirshleifer (1989) pp. 10, in fact, affirms that "since the high private marginal opportunity rates have no bearing at the social level, government investment projects should be evaluated at the lower market interest rate appropriate for riskless investments".

al. (2008) say that the classical approach of cost-benefit analysis through Net Present Value (NPV) methodology seems problematic when long-term and uncertain periods and elements are considered.

Just as climate change is caused by actions taken today, but will be felt by generations to come. The costs of avoiding it are incurred today, while its positive effects also felt only in the future. However, as explained by Weitzman (2010) and Gollier & Weitzman (2010), the logic of positive constant interest rates tends to lead us to think that earth-shaking events, even an atomic bomb or the Arctic glacial melting, might not matter much today if they were to occur many generations ahead from now. In that sense, very small variations in exponential discounting rate adopted to evaluate projects for very long periods may affect greatly the results, hence making the cost-benefit analysis discredited, as any hypothesis could be defended using a specific discount rate.

Therefore, it is quite important to punctuate two basic elements that shall be considered when evaluating climate change policy, both related to the long-time horizon in which the analysis is made: the first one is that, under the classical cost-benefit NPV approach, current generations and short-term investment decisions will be favored over long-term climate change-related investment decisions. The second one is that this kind of analysis will bring in itself some degree of uncertainty since the more distant the time horizon considered is, the less it is known about it. These elements lead economists and analysts to be cautious when performing cost-benefits analyses (CBA) under a classical approach, as results might be misleading.

Hence, in an effort to address those particular issues of climate change analyses and turn climate change policy CBA more reliable, several studies discussed methods and discount rates that would better reflect climate change issues and specificities (Dasgupta et al. 2000; Weitzman 1998; Gollier et al. 2008; Sunstein & Weisbach 2008). The question to be answered is how to avoid underestimating climate change impacts, mitigation investments benefits and future uncertainty?

This section will provide a brief summary of the main literature references regarding these discussions in order to elucidate about the debate of discounting under the climate change debate. This literature review is important as it gives the conceptual basis for discount rate choices and paths to be adopted in the integrated modeling approach followed in this thesis.

3.2.1 Defining Discount Rates Under the Climate Change Debate

Intergenerational discount rates have been brought to debate not only under the climate change light, but also under economic growth, energy policy, nuclear waste, and major infrastructure programs (Nordhaus 2007). However, and this will be the focus of the discussion in this chapter, the climate change debate has been the main gear of this issue in the last few years, especially after the study published by Stern (2007), which considered the intertemporal discount rate as one of the important issues when evaluating the global cost of climate change.

First, it is important to punctuate the role of climate change in economic analysis, i.e., how it is treated by economists. As explained in Stern (2007), the climate is treated by economists as a public good and human-induced climate change as an externality. As an externality, it means that agents who generate climate change, by whatever means, like generating electricity through fossil fuels, burning forests, producing steel, etc, do not pay any price for generating climate change as a ‘secondary product’ of their main activity. However, climate change cannot be treated as a conventional externality, as it has some specificities that makes it harder to deal than other environmental externalities. Its main characteristic is that it is global in its causes and consequences and the latter is prolonged for many years ahead, affecting many generations. Also, for being of long term, the impacts of climate change are uncertain, and quantification of economic effects and irreversible changes are imprecise (Stern 2007).

The Stern review (Stern 2007) was released in 2007 and had as its main objective the evaluation of the economic impacts of climate change through a broad range of evidence and the assessment of their economic costs through different techniques. Also, the review assessed the economics of stabilization and the challenges of policies responses to mitigation and adaptation in the global level. For what is worth to this literature review, it is important to mention that the review takes a consistent approach towards uncertainty, focuses on a quantitative understanding of risk and takes a systematic approach to the treatment of inter- and intragenerational equity, taking into consideration various ethical perspectives in the context of climate change.

When it comes to discounting, the review uses an approach based on the sum of utilities of consumption taking into consideration that the effects of GHG emissions will be felt by the generations of the future. The main ethical issue the study brings to light is about judging if a unit of consumption has more utility at the present or at the future. As in the classical theory, an increment in future consumption is considered of less value than an increment in present consumption either because of ‘pure time preference’ or because if consumption grows now, people are better off in the future and, being better off in the future, the marginal utility of consumption is worth less (Stern 2007).

On the other hand, pure time preference should be put into a relative perspective once generations very distant in the future should also be represented. This is very important in the climate change debate, since the effects of what is done today will be felt by future generations. In that sense, Stern takes, as himself affirms, a “simple” approach considering that future generations have the same claim as the current one. This is a prescriptive approach that, when reflected in the discount rate chosen, means that their consumption should not be discounted. This, as a result, gave the very low discount rate adopted in the study, 0.1% per year, that was criticized after the review was published.

One of the main critics of the Stern review was Nordhaus, that published in 2007 an examination of Stern’s review (Nordhaus 2007), affirming that the alarmist results of the review was a direct consequence of the near-zero discount rate adopted in combination with a specific utility function. Stern uses the argument that positive discount rates would cause societies to ignore high cost in the long-term future, hence, underestimating global warming impacts caused by human activity (Stern 2007). The main criticism to this is the argument that it is based on a prescriptive approach, in which the decision of time discounting and time elasticity was chosen based on the authors point of view and their ethics. From Nordhaus point of view, and he shows that this change of thinking has great impact on the results in terms of costs of climate change, the approach of the evaluation should be based on real interest rates and real market expectations (Nordhaus 2007).

To understand this issue better, it is important to mention that Stern and most economists discussing climate change and global warming (Dasgupta 2008; Goulder & Williams 2012; Sunstein & Weisbach 2008; Gollier et al. 2008) use the theory of economic growth under the approach of Ramsey-Koopmans-Cass model, or just the “Ramsey model”. Nordhaus (2007), pp. 12, defines it as “a central decision maker desire to maximize a social welfare function that is the discounted value of utility of consumption over some indefinite time period.” In a simpler definition, Baum (2009) says it is designed to assess tradeoffs between present and future consumptions. The simple form of the equation is:

$$r = ro + ni*g$$

(Equation 3-2)

in which:

r: consumption discount rate

ro: utility discount rate

ni: elasticity of consumption in relation to utility

g: growth rate of consumption

Basically, the equation indicates that wealth can be either spent today through consumption or invested in order to generate future growth. Arrow et al. (2013) illustrate well the meaning of *ro* and *ni* in (Equation 3-2): *ro* is the rate at which society, or the social planner, discounts the utility of future generations and if it is considered to be zero, then the utility of future generations is worth the same than utility of current generation. *ni* describes the variation of marginal utility of consumption as a function of consumption, indicating how fast the former falls as the latter increases. Moreover, the equation is a mathematical way to say that utility of consumption of future generations should be discounted at a higher rate because they are expected to be wealthier, assuming the growth rate of consumption is positive. At least, this is the commonplace interpretation and future consumption will be discounted at a higher rate the highest is the value of *ni* (Arrow et al. 2013).

Dasgupta (2008) says that *ro* and *ni* are important parameters when defining discount rates as they help determine how society ought to discount changes in future consumption. The choice of *ro* and *ni* are the key difference between studies either in terms of results of models, as occurs between Stern (2006), Cline (1992) and Nordhaus (1994), or in terms of ideology, as occurs between Bauer (1957), Nordhaus (2007) and Authof et al. (2008), all descriptivists, and Ramsey (1928), Stern (2007) and Dasgupta (2008), the three of them prescriptivists.

3.2.2 Declining Discount Rates (DDR)

It is important to highlight that neither Stern (2007) nor Nordhaus (2007), which are very important references in the economics of climate change debate, adopted declining discount rates in their analysis. However, this discussion has emerged almost always under a very economic and mathematical approach with focus on avoiding the underestimation of possible future welfare loss of generations to come due to climate change effects.

The challenge is posed towards a situation under which one should choose between acting today expecting immediate benefits or in the long term, i.e., in attributing a smaller or higher value to the future. However, the more distant the future is, more uncertain and harder to predict it is. Hence, it is important to address how to consider this uncertainty when making cost benefit analysis under long time periods, like when evaluating climate change effects. Moreover, how to attribute a proper value to the future, considering the discussion made before, i.e., that as future generations will feel the impact of climate change, they could also be better off than current generations due to consumption growth, is also a challenge posed within this context.

Goulder & Williams (2012), after a discussion about two different concepts of discount rates when evaluating climate change (the social-welfare-equivalent consumption discount rate and the finance-equivalent consumption discount rate), evaluate how uncertainty affects discounting. The authors explain that potential benefits in climate change policies are uncertain and that this uncertainty is correlated with uncertainty of consumption growth: if this correlation is negative, then benefits are maximized by low levels of consumption and vice-versa. This uncertainty might be handled by using 'expected benefit' approach combined with adjustments in the discount rate to deal with risk, or by using the 'certainty-equivalent benefit' approach, in which uncertainty and discounting can be analyzed separately (Goulder & Williams 2012; Weitzman 1998).

The equation below is a way to adopt the 'certainty-equivalent' approach:

$$(1+r^{*})^{-t}=\sum_{j}[p_{j}(1+r_{j})^{-t}]$$

(Equation 3-3)

Where

r^*: is the certainty- equivalent rate

r_j: discount rate at a state of nature j

p_j: probability of state of nature j

Under this approach, all possibilities of discount rates are collapsed in r*, that should give proper results when used to discount future benefits. It is important to note, however, that (Equation 3-3) yields a r* that is not constant over time. It can be observed that for t=1, (Equation 3-3) assumes the Ramsey equation form, as in (Equation 3-2), but as the value of t grows, r* tends to a minimum value. This, finally, leads to the conclusion that, when dealing with uncertain and long-term horizons, the certainty-equivalent discount rate equals to the lowest possible discount rate. Goulder & Williams (2012) explain that on discount factors: they will be smaller as higher is it. This affirmation is also supported by Gollier & Weitzman (2010) while they discuss and solve the so-called "Weitzmann-Gollier" puzzle and have as bottom line the affirmation that "there is a generic rigorous argument that the future should be discounted at a declining rate that approaches asymptotically its lowest possible value" (pp. 351).

Weitzman (2010)'s approach on discounting the long distant future combines the 'gamma discounting' with the Ramsey model, an intertemporal optimizing model, in order to 'risk-adjust' probabilities by marginal utility weights. The author makes future discount rate a function of time based on the premise that uncertain production function is a random variable whose probability density function (PDF) is a gamma distribution[21], and the gamma PDF combines well with exponential discounting to create an expression for the certainty-equivalent discount factor. Instead of consumption growth, the author considers the future productivity of capital the primitive driver of future discount rate and shows mathematically that, in that case, when future productivity is uncertain, the higher is the value of risk aversion (*ro* in Ramsey model), the lower is future discount rates, opposing conventional deterministic wisdom. In the study, a few simple exercises show that even very moderate risk aversion elements may increase the risk-adjusted probability of low-productivity states, since they enhance the effect of gamma discounting. Hence, the probability weight of scenarios with low discount rates and low endogenously-chosen consumption levels are leveraged.

Another study, by Gollier et al. (2008) used declining discount rates to assess the willingness of current generation to pay for very distant benefits, which should give a signal about where to go in terms of projects and policies. In a more sophisticated mathematical demonstration, they showed that a prudent agent would be willing to sacrifice a larger fraction of current wealth to improve uncertain future by reducing the discount rate in CBA

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[21] The author has chosen the gamma distribution mainly due to its analytical tractability (Weitzman 2010).

analysis. Their methods combine a model that describes this behavior and very long historical data that detects the characteristics of interest rates series. In this sense, they estimate a theory-consistent schedule of declining discount rates (DDR) for nine countries to be used in CBA climate change mitigation policy. Their results show that, indeed, the adoption of DDR in CBA may change social planner behavior, making him improve social welfare in the distant future.

In 2012, a study named "How should benefits and costs be discounted in an intergenerational context? The views of an expert panel" (Arrow et al. 2013) presented results from a survey with specialized economists, summarizing the results on how the benefits and costs of environmental regulations, including climate change, should be discounted when they consider projects affecting future generations. Results show that there was a consensus on the fact that Ramsey rule is a useful methodology for intergenerational discounting and that there are enough arguments showing that declining certainty-equivalent discount rates should be used under uncertainty future analysis. However, it was shown that there is not an agreement on how to estimate the parameters of Ramsey's equation among all economists, since, indeed, there are different approaches, as already discussed, and the practical identification of those parameters may be quite challenging. Also, when it comes to DDR, the estimation of a certainty-equivalent discount rate pathway is equally challenging and depends on *ro*, *ni* and g. There is, as an alternative, the expected net present value approach, that, according to the authors, is the gamma discounting approach discussed previously.

As it can be observed, studies on how to discount long-term future in the context of climate change have been improving wisdom around this debate continuously. As mentioned by Arrow et al. (2013), countries in Europe, like France and UK, already adopt the DDR methodology in their environmental analyses and the fundamental challenge still is how to estimate the key parameters in order to establish adequate consumption growth perspectives, marginal utility relative to consumption and time preference. Since Brazil has recently engaged in climate change commitments in the sense of establishing mandatory emission reduction targets, analysis under DDR approach should gain space in Brazilian policy discussions in order to address intergenerational issues and time preference as long-term horizons are considered. Thus, in the next chapter a methodology of integrating assessment with the adoption of DDR will be considered in order to evaluate the impact of discount rate choice on Brazil’s energy system development.

3.3 Other Temporal Issues Related to Climate Change

Although not directly related to time preference as the discount rate choice is, some issues might impact the time preference of public and private agents by delaying or anticipating the moment of investment in low carbon technologies. The first of them is the lock-in phenomena, in which some technologies are preferred over others due to their historical adoption and, hence, they threaten the penetration of new technologies due to inertia of the system. The second is directly linked with the imperfect global context regarding climate change mitigation: as the climate agreement has to reach the global level due to its nature, it is expected asymmetries regarding the level and timing of commitment of different regions. This might happen due to the financial capacity of distinct regions (developed, developing and undeveloped countries) and to the recognized historical responsibility of some regions over others about historical GHG emissions.

In this section, these two issues will be exposed and discussed, as they were used in this work as parameters to set different scenarios regarding timing of investment, as will be discussed in chapter 4. In fact, all these elements usually act combined and impact significantly the investment decision of firms and how governments deal with the deployment of public policies to overcome eventual barriers that these elements might incur.

3.3.1 The Timing of Investment and the Consequences of Technological Lock-In

“In an essential sense, innovation concerns the search for, and the discovery, experimentation, development, imitation, and adoption of new products, new production processes and new organization set-ups” (Dosi 1988: pp. 222). Innovation has a very important role in the climate change issue because it paves the way of new low carbon technologies towards economic feasibility by lowering costs progressively (Haščič et al.

2010). To this purpose, policy instrument mechanisms might be put in place in order to foster innovation and to promote mitigation, as discussed in item 2.2.2[22].

However, the success of innovation policies under the innovation system[23] approach might be hampered by a series of barriers, such as short-term political processes, fragmented governance structures, technological trajectories and lock-in, market power and political clout of incumbents, lack of consumption acceptance/adoption and institutional inertia and path dependency (OECD, 2015). In sum, all these elements are intrinsically inter-related and they constitute challenges to be overcome in order to enable new technologies, as the current technological system usually is stuck to technological, logistical, institutional and social conditions.

Perkins (2003) exposes as the central idea of “lock-in” the fact that technologies and technological systems[24] might follow pathways that are difficult to scape because they are built on past achievements, ideas and knowledge, which can have powerful exclusion effects. That path-dependency relies in the phenomenon of increasing returns, which is defined as the positive feedback mechanism that makes a technology more attractive to adopt the more it is adopted. In that context, it can be inferred that there are benefits accrued from early adoption of technologies, as stated by Arthur (1989) and David (1985). In fact, preferred technologies, i.e., the one adopted earlier, tend to benefit from improvements than their competitors, which leads to further adoption, further improvements and leadership, even though they might be at start inferior technologies[25] (Perkins 2003). Increasing returns usually are more influent in the early phases of learning and competition, when positive feedbacks can give a technology with the right timing and favorable conditions advantages that can make it dominant (Arthur, 1994).

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[22] OECD (2012) constitutes a report of innovation case studies through public policies in different countries.

[23] An innovation system is a heuristic concept that considers and analyses all societal subsystems, actors and institutions contributing in one way or the other, directly or indirectly, intentionally or not, to the emergence or production of innovation (Hekkert et al. 2007).

[24] Technological system is defined as a set of inter-related components connected in a network or infrastructure that includes physical, social and informational elements (Unruh 2000).

[25] A classic example of this situation is the QUERTY keyboard, that was a less efficient configuration when compared to DSK, but predominated as the main keyboard configuration (David 1985).

Foxon (2002), based on Arthur (1994), list four major classes of increasing returns: scale economies, learning effects, adaptive expectations and network economies. Scale economies is related to the well-known concept of inverse proportionality of fixed costs per unit and quantity produced, which means that unit production cost declines as production rises. Learning effects come from what is defined as "learning-by-doing", which is the consequence of repetitive efforts and reduction of time to produce one unit of a commodity[26] (Anzanello & Fogliatto 2011). Adaptive expectations arise when increasing adoption reduces uncertainty, which increases the confidence of consumers and producers about quality, performance and permanence (Arthur, 1994). Finally, network economies occur when advantages derive from the adoption of the same technology by different agents. Foxon (2002) gives as example the case of mobiles in the telecommunication as the more people adopt them, the more advantageous is for one individual to adopt it as well.

Existing and consolidated technologies commonly have "sunk costs" (irrecoverable costs) because investments on them were made in the past by firms. Hence, these firms will show some resistance to invest in new technology alternatives that will not benefit from these sunk investments. This is true in the energy sector, in which high amount of investment are involved and agents are frequently looking for "no-regret" options[27]. This has direct effect on investments in mitigation options, since industrial economies have been locked-in into fossil fuel-based energy systems. Unruh (2000) defined this condition as "carbon lock-in", explaining that it creates persistent market and policy failures that may inhibit the diffusion of carbon saving technologies despite their apparent environmental and economic advantages. Indeed, the author points out that the inability of governments, and society in general, to take even precautionary action to date is a result of carbon lock-in.

Carbon lock-in arises from systematic interactions among technologies and institutions. In order to understand these interactions, Unruh (2000) introduces the notion of

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[26] This effect can be mathematically translated into learning curves, which shows the unit cost declining with cumulative production (Anzanello & Fogliatto 2011).

[27] In the GEE mitigation context, no-regret options are the one with negative costs, i.e., the generate direct or indirect benefits, such as market failure reductions, double dividends through revenue recycling and ancillary benefits, large enough to offset the costs of implementation (IPCC, 2001).

techno-institutional complex (TIC), which is developed through a path-dependent, co-evolutionary process involving positive feedbacks among technological infrastructures and the organization and institutions that create, diffuse and employ them. Also, he affirms that it is a natural process that firms prefer to focus on existing competencies and away from alternatives that may lead their present products to obsolescence. In this context, capital investment is directed to perfect existing products and reinvest in dominant design competencies.

Moreover, the same author (Unruh 2002) explains that public policy and private investments are made under limited foresight and they tend to discount potential future risks and disutilities. In that context, unintended consequences may become lock in in the TIC, as happens with the climate change impact derived from fossil-fuel use: investments in the fossil-based system have happened for years, since the climate change issue was still unknown (myopic foresight). Now that this issue is broadly recognized, the energy system is locked-in a carbon based system and it directly impacts how fast the system reacts to this new issue and gets transformed to overcome this problem.

Repeated investments lead to the technological lock-in at a firm level, indicating that rarely firms would risk invest in radical innovation (Lovins 1998, Foster 1986). However, lock-in effects may have a broader nature as systemic relations among technologies, infrastructure, industries and users create positive feedbacks that creates value across physical and informational networks. Financial institutions can further reinforce the lock-in effect by being risk-averse when granting credit, as well as social behavior that co-evolves with dominant technologies and create inertial perspective, expectations and preferences.

Moreover, the intervention of the government may intensify the lock-in created by technologies, institutions and individuals. In fact, government intervention can remove market uncertainty related to technological development through policy and, hence, favor a specific design. On the other hand, as the involvement of government institutions can have long-term impacts, lobbying officials might claim for support and preferential treatment of an existing technological system (Unruh 2000).

Rational corrective policy actions in the face of climate change would include the removal of perverse subsidies and the internationalization of environmental externalities arising from fossil fuel use. Indeed, the difficulties of governments in dealing with outdated and counterproductive subsidy programs are also an indicator of carbon lock-in (Unruh 2000).

In another study, the same author (Unruh 2002) discusses ways of escaping carbon lock-in, indicating that exogenous forces are necessary to promote this. The author divides ways of escaping the carbon lock-in in three approaches: end-of-pipe, continuity and discontinuity.

The least impacting solution would be the "end-of-pipe", as it does not incur in any changes in the infrastructure in place. Instead, offending disutilities are treated with add-on technologies, commonly in the output side of the system. In the climate change context, it would mean controlling emissions through non-value adding changes that allows to control process output (emissions) without changing the process (Unruh 2002).

When the path-dependency of the system is still respected by working within the limits of the technological evolution, the escaping effort is considered to be an incremental innovation or change. The change is limited to a number of offending subcomponents, focusing on component or intra-system innovation (Hunter et al. 1994). This is called continuity as it aims at maintaining the current configuration of the system as much as possible (Unruh 2002).

In turn, the discontinuity consists in a radical change where an existing system configuration is completely abandoned on behalf of a superior system. New technologies may play an important role under both continuity and discontinuity policy approach, as the example of wind and solar power, that may offer a continue transition by their incremental connection in the electric grid or may cause a discontinuity by decentralizing electricity generation and discarding the electric grid (Unruh 2002).

After exploring these approaches towards lock-in, Unruh (2002) discusses about how incumbent firms are rarely responsible for innovation and, because of that, a technological breakthrough has to arise not only due to technology-push, but also due to market-pull. In that sense, it states that "innovations tend to emerge in small market segments where their unique attributes are valued and early performance limitations are less of a drawback" (p. 322). Under this context, the establishment of niche markets proves to be attractive as sales volumes are low and not attractive to incumbent firms, which removes some resistance of the dominant system. As market grows slowly, improvements on technology and gains of scale might unlock the system.

A second possibility of attempting to escape the carbon lock-in happens via institutional change, by facilitating the recognition of environmental degradation caused by the fossil fuel based system at social and political level (Unruh 2002). The main idea would be to create a social consensus for policy action and improve public acceptance of new technologies.

Either way, as the problem of carbon lock-in is overcome, it becomes clear that the more the system is rooted in one specific configuration (such as the fossil based one), the more difficult it is for new technologies to penetrate the existing market due to the inertia of the current energy system. This inertia is derived from the lack of good will from incumbent firms to lose the market share of current technologies and from social consensus about current technologies. This also leads to weak near-term low carbon policies, which might end up reinforcing the carbon lock-in and turning mitigation efforts to end-of-pipe and continuous options. Some studies explore these effects, such as Johnson et al. (2015), Vergragt et al. (2011); and Bertram et al. (2015). Hence, even though there are low carbon options available to invest, their entrance in the system tends to suffer resistance by the system and this impacts the timing the new investment occurs. Moreover, as the lock-in effect tends to threaten and cause delays in low carbon investments, the ways chosen by government and firms to act policy and investment wise, also impacts, delaying or anticipating the low carbon transition. Under this approach, the lock-in effect is considered in this work, as it will be shown in chapters 4 and 5.

3.3.2 International Cooperation towards Climate Change: Early and Delayed Action

There are plenty of studies in literature exploring the fragmentation of different regions when committing to climate policy at a global level. This is due to the differentiated effort sharing, which leads to distinct commitment levels based on an equity principle of common but differentiated responsibilities and respective capabilities, already discussed in chapter 2. Many effort sharing approaches have been proposed and discussed in the literature. Differences are related to participation levels, timing of reductions and stringency and type of commitments. This differentiation across regions aims at mimicking the imperfect political context under which climate negotiations have been taking place in the last few years (Clarke et al., 2014). In this work, this uncertain environment is considered to possibly impact Brazil's energy system and mitigation commitments in the mid and long-term. The approach adopted is focused on the timing of mitigation efforts, since, as a developing country, Brazil might hold a less stringent commitment towards reducing climate change and it may delay its mitigation efforts[28].

Clarke et al. (2014), in the most recent assessment report of IPCC, acknowledges that considering the idealized assumption of cost effective scenarios, i.e., that mitigation happens where and when it is least expensive, is a distortion of reality, since countries tend to take on mitigation at different times and using different and independent implementation approaches. The authors point that usually the implementation under non-idealized includes near-term mitigation inconsistent with the long-term goal of 450 ppm CO_{2eq} in 2100 and the differentiation of carbon prices across countries, leading to a situation where some countries reduce emissions more aggressively than others, since a group of countries will have early participation and others will have delayed participation on climate commitments.

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[28] It should be highlighted 2 aspects in this sense: 1) As it will be mentioned in this section, the effects of effort sharing might lead to delayed action or to less stringent policy in terms of reduction targets (cumulative or per period). In this work, it was only considered the first option, since it is of interest to consider the impacts of eventual changes in timing of investment; 2) It is acknowledged that Brazil has already made commitments related to mitigation to 2030 once it has signed the Paris Agreement. Hence, the inclusion of alternative scenarios that considers mitigation efforts later than 2030 are an exercise to identify the effects of delayed action if Brazil did not commit to the agreement or if it fails to comply with it.

It can be observed from the literature that this issue on non-idealized implementation of low carbon policies have been approached in distinct ways in terms of policy premises across studies and that the multi-model methodology has been widely used. Here some of these studies will be cited.

Some IAM studies exploring the impact of delayed action in terms of climate policy to reach the 450 ppm goal found that this stabilization level may be reached by the end of 2100 with some consequences such as greater forcing overshoot[29], greater dependence on negative emissions (mainly through BECCS) and greater institutional challenges after the adoption of the long-term target. Luderer et al. (2013) showed that regional mitigation costs are highly dependent on the choice of model and regime, pointing the need for research on regional mitigation costs and compensation mechanisms, which somewhat turns out to be a driver for this thesis and also a suggestion of future work. They reach to this conclusion by considering three global integrated assessment models to evaluate current[30] (and considered weak) climate policies on long-term mitigation targets. Tavoni et al. (2013) recognizes that achieving climate stabilization consistent with the 2°C objective is influenced by how policy efforts (mitigation and economic wise) will be distributed among economies. In this context, they consider different allocation schemes in terms of mitigation commitments worldwide under a multi-model quantification approach. The main conclusions show that a homogeneous carbon pricing at global level would incur in a higher burden (in terms of policy costs) to developing countries and energy exporter countries and a lower burden to OECD countries. To deal with that problem, an allocation scheme based on the equalization of policy costs across regions would be needed.

Kriegler et al. (2013) assess possible Durban platform[31] outcomes, the latest discussion on climate at the time, for a post-2020 architecture, under the LIMITS project. The main idea was elucidating the relation between near term mitigation actions and the 2°C limit long-term target, as low ambition short-term targets lead to a delay in the climate effort

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[29] Overshoot happens when a final concentration stabilization level is temporarily exceeded.

[30] Mainly based on the Durban platform.

[31] The authors (Kriegler et al. 2013) explain that the Durban Conference in 2011 established a platform to start negotiations on a new international climate treaty (post- Kyoto) post-2020.

necessary to reach the 2°C goal. They highlight that once fragmented near-term climate policies are assumed for a period, big challenges arise to implement long-term more ambitious targets because of the need for steep reductions of emissions intensity and transitional and long term economic impacts. The system will have to rely heavily on negative emissions through BECCS[32]. Moreover, the emission gap between delayed and immediate action depends mainly on the stringency of the near-term action and the choice of the long-term target and the magnitude of the emission gap and the emissions intensity decline rates in scenario results somewhat indicate the challenges that adopting a long term target might bring: in sum, the larger the emission gap, the grater the implied emissions intensity decline rates, increasing the mitigation challenge.

Schaeffer et al. (2013), within the AMPERE project, focus on scenario variants that deviate from the idealized assumption of immediate full cooperative action on meeting stabilization targets. In this context, they explore a delayed action situation where short-term policies (until 2030) are moderated in their stringency and the long-term target (compatible with 2oC commitment) is put in place thereafter. Moreover, they also explore a staged accession to a global climate regime, where some countries commit to policies later than others. The study provides insights in the sense that emissions by 2030 at high targets need to be more rapid and deeper compensated through emission reductions after 2030, as results for delayed actions scenarios indicate that rate of warming around 2040 may be up to 50% higher compared with optimal scenarios. Riahi et al. (2015) also published results related to the AMPERE study with a similar set of scenario premises, but focusing on costs and feasibility of the transformation. They show that 2030 mitigation efforts comparable to Copenhagen and Cancun agreements may result in a lock-in of the energy system into fossil fuels and make it difficult the transition towards low greenhouse gas stabilization levels.

Bosetti et al. (2009) assess the role of immediate against delayed participation of developing regions in an international climate agreement. This study focus on the macro-economic policy costs and in the role of innovation, adoption and diffusion in promoting transition in developing countries by using as modeling tool a hybrid energy-economy-model

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[32] Bio-energy with carbon capture and storage.

(WITCH). It is interesting to note the scenario approaches the authors adopted to evaluate the effect of different commitment levels and configurations: they considered four stabilization targets (in terms of radiative forcing) in 2015; immediate participation, where a uniform carbon tax is applied, and myopic delayed participation of developing countries when BRICS engage in 2030 and other non-developed countries in 2050; and policy anticipation, which has to do with the foresight of non-participating countries and consists in fixing all variables of late participants to their business-as-usual scenarios values, implying that developing countries do not foresee not anticipate climate policies, which is received as a shock. The main outcomes of the study show that delayed participation of fast-growing countries increases the cost of climate policy and that the optimal investment strategy for developing countries is to anticipate policies for around ten years and incorporate future carbon prices in short-term energy investment decisions.

Clarke et al. (2009) also explores the dimension of international participation in emissions mitigation through a multi-model approach, i.e., considering a set of different models to generate comparable scenarios that would shed light on the influence of different concentration target commitments, the possibility of overshoot and the delayed participation of some regions. Ten global models (part of the EMF 22 International Scenarios) were considered and the delayed participation premise was in line with Bosetti et al. (2008)'s, in which Annex one countries would engage in climate commitments before 2015, BRICS countries would engage after 2030 and other countries would engage after 2050. Results confirm some intuitive conclusions, as the challenge to mitigate increases with the concentration target even with overshoot and immediate and comprehensive international action. Also, as some scenarios did not cope with more stringent targets under delayed participation, it is possible to assume that efforts to meet ambitious low carbon targets might be constrained by a failure to develop an international engagement in climate mitigation.

As shown by these studies, the delayed and fragmented participation in global low carbon commitments are commonly approached with integrated assessment models at a global level, grouping countries in blocks based on their economic development level. Hence, they provide an assessment of regional impacts under a global emission reduction scheme, commonly providing as results relative emissions and cost increases caused by these scenarios. Often, specific countries are not detailed enough and it is not possible to evaluate impacts at a country level considering the detailed technology mix and specific parameters such as investment costs. As they have the advantage of identifying interactions between regions and markets, they fail to consider particularities of specific countries, leading to uncertainty regarding emission and cost outcomes. This motivates the development of country level studies, which identify more precisely the impacts of national policies under different global commitment contexts (immediate or delayed) on the national energy system.

It can be also observed from the studies mentioned in this section that there are different approaches to reflect delayed action in integrated models. The delayed participation may be expresses as weak near-term policies that compromises more stringent long-term commitments, it may be reflected in timing of policy, i.e., when it begins and/or it may be reflected in different commitments of different regions, when global models are considered. For the purpose of this thesis, the possibility of fragmentation related to global climate policy is considered under the premise that Brazil might delay its commitments towards a global climate policy by starting to act later than other regions, mainly developed countries. The relative effect is not perceived, but the impact of delayed action on the energy system might be identified. Moreover, it can be said that this approach is the most interesting one when the main goal of this work is evaluating timing issues, mainly reflected in time preference) and their impacts on climate change policy in Brazil.

4 Methodology

This chapter presents the methodology adopted to evaluate how discount rate choice might impact climate policy in Brazil. As a first step, however, a literature review associated with integrated assessment models for energy and climate policy analysis will be made in the first section in order to put into context and to justify the adoption of a IAM tool in this work.

4.1 Background: energy systems models.

Integrated assessment models (IAMs) are defined as 'approaches that integrate knowledge from two or more domains into a single framework (Nordhaus 2013). Kelly & Kolstad (1998) say that they combine the scientific and economic aspects of climate change in order to assess policy options. Van Vuuren (2015) affirms that they are "integrated" because they integrate information in order to incorporate all relevant aspects (economics, technology, climate knowledge) and it refers to "assessment" because it explores or estimates pathways in order to answer policy questions. In that sense, IAMs are designed to describe interactions between human and environmental systems, and not to make predictions (Van Vuuren 2015).

There are several types of IAMs, ranging from small cost benefit analysis (CBA) models to complex models able to identify underlying processes of interaction (Van Vuuren 2015). Ortiz & Markandya (2009) affirm that IAMs may be classified in a number of ways. Toth (2005) divides IAMs in policy evaluation models, i.e., those simulations models that apply exogenous assumptions of policy course to variables of interest to the policy-maker, and policy optimization models, i.e., those determining the values of key policy variables in an optimization procedure. Stanton et al. (2008) divide IAMs in four groups: welfare optimization models, based on net present value (NPV) maximization subject to climate constraints; general equilibrium models, based on a set of demand and supply functions; simulation models, based on exogenous scenarios; and cost minimization models, based on optimization and cost-effectiveness. It can be observed that there is some overlap between different classifications, with models that fit into more than one category (Ortiz & Markandya 2009).

In the energy field, the adoption of IAMs to scenario evaluation in order to support policy-making has been popular since the 1970s, when planning was needed to deal with the first oil crisis (Kok et al. 2011). In fact, the role of energy modeling in improving the evidence base underpinning policy decisions is being increasingly recognized and valued (Chiodi et al., 2015). Chiodi et al. (2015) and Gargiulo and Ó Gallachoir (2013) say that there is a wide range of energy modeling tools, like simulation, optimization, partial equilibrium, general equilibrium, sectoral demand, single technology, etc, being possible to classify several of them under IAM category.

Notwithstanding, a common distinction made in the energy field for models is between economic or top-down and engineering or bottom-up models according to how the energy system is represented (Greening et al. 2007). Most of these models, in general, use a dynamic modeling framework and they simulate the impact of climate change in the economy. Economic models are, in general, computable general equilibrium (CGE) models. They consider energy demand as a function of energy prices, income and climate variables by adopting a standard economic demand equations (Ciscar & Dowling 2014). Since CGE models are out of the scope of this thesis, they will not be detailed in this chapter[33]. Engineering models are technology-rich, commonly least cost future energy systems pathways and they have been used extensively to evaluate energy transitions to a secure, low carbon future (Chiodi et al. 2015).

Energy models adopt theoretical and analytical methods under an interdisciplinary approach, henceforth including not only engineering issues, but also economics, operations research and management science issues. Also, different techniques might be applied, such

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[33] For more information about CGE models, see Ciscar & Dowling (2014); Roson & Mensbrugghe (2010); Eboli et al. (2004) and Jorgenson et al. (2004).

as mathematical programming, especially linear programing, econometrics and statistics (Chiodi et al. 2015; Hoffmann and Wood 1976).

The main advantage of bottom-up energy systems models is that their approach includes interactions within the system, like the competition between conversion processes and the energy commodities, leading to the need of a high level of technology detail (Chiody et al. 2015; Fais and Blesl 2015). Moreover, they provide insights into the most important substitution options that are linked to the system as a whole. In fact, by considering energy supply and demand across different sectors at the same time, they may help private decision-makers properly in terms of cost-effective investment decisions and their indirect effects on the system, as well as public decision-makers on policy decisions in terms of technology diffusion (Chiodi et al. 2015).

Fais and Blesl (2015) say that because of the high technological detail, bottom-up models are, indeed, the only approach to be adopted to evaluate the effect of technology-specific measures and to identify the impact of new technologies with no historical data, such as carbon capture and storage or hydrogen-based technologies for energy generation. This is important to consider when discussing climate policy impacts on energy systems because of the technology transition the policy may lead to, making viable ‘breaking through’ technologies that were never adopted before.

Regarding studies that adopt IAM and energy systems modeling to evaluate climate change impacts, there are many in literature, indeed, that evaluate climate policy in the light of scenario analysis, especially at global level. Not all of adopted IAMs are energy system models[34], but they might have energy system as one of their facets. Riahi et al. (2015) makes a model comparison (nine models in total) aiming at evaluating the implications of near-term policies for the costs and attainability of long-term climate objectives. They conclude that mitigation efforts in 2030 comparable to the 2012 Copenhagen pledges result in a further lock-in of the energy system into fossil-fuels and makes it difficult the transformation required to reach low GHG stabilization levels, as discussed in section 3.3.2. Bosetti et al.

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[34] They might be climate models or land use models, for example.

(2009), also mentioned in section 3.3.2, investigate the best short-term strategy to be adopted by emerging economies in order to follow OECD countries' mitigation effort, given the common long-term goal of preventing global temperature increase without compromising economic growth. They use a hybrid global level energy-economy model (WITCH) and they conclude that delayed action could incur in economic losses for emerging market and that optimal behavior would be anticipation. Schaeffer et al. (2013) get similar results when assessing a set of scenarios into a framework to analyze consequences of delayed near-term action and staged accession scenarios for limit warming below $2^{o}C$. Van Vuuren et al. (2009) and Calvin et al. (2009) also consider IAMs to evaluate mitigation potentials and mitigation costs, respectively.

Regarding models at national level, Fais and Blesl (2015) overview the use of bottom-up energy system model TIMES to evaluate the long-term effect of energy and climate policy instruments in Germany. They elaborated scenarios of climate policies with a cap-and-trade and scenarios of energy policies with different support schemes for renewable electricity as a case study and they stress that the choice of modeling tool and the level of the detail should always depend on the question to be answered. Another national level study, by Simoes et al. (2015), uses TIMES model applied to Portugal in order to quantify how assumptions like economic development and technology evolution influence the outcomes of scenarios. It concludes that some assumptions, like availability and price of energy resources, do not influence that much GHG emissions. Napp et al. (2014) also adopt TIMES model, now applied to South Africa (SATIM model) to model energy consumption and CO_2 emissions of the country industry sector under different carbon prices and economic growth rates.

Brazil's energy system has also been evaluated through the adoption of energy systems modeling. The first country profile obtained with integrated modeling was made by (IAEA 2006) and de Lucena et al. (2010) used MESSAGE model applied to Brazil aiming at evaluating energy system's adaptation to long-term climate change scenarios. Afterwards, the same model was updated and used to evaluate the integration of wind (Borba et al. 2012) and solar power (Malagueta et al. 2013) in the country's electric power grid and to evaluate the role of carbon capture and storage in Brazil's future electricity generation (Nogueira et al. 2014). More recently, Lucena et al. (2015) considered the result of six models (energy-economic and IAMs) up to 2050 in order to assess the effect of market based mechanisms and carbon emissions restrictions on Brazil's energy system. Meanwhile, Herreras Martínez et al. (2015) compared a national level model with two regional (Latin America) models to assess trends for energy emissions in Brazil (and Latin America) based on scenarios consistent with the 'no more than 2ºC temperature increase' target.

All these studies consider different IAMs with different rationales, geographical frontiers, parameters and goals. Clarke et al. (2014) says that the adoption of multi-model analysis brings uncertainty down and provide insights on the effects of specific parameters on scenario results. Indeed, different models tend to complement each other with their different responses, giving different types of information like trading, technology pathways and GHG emissions for different regions, under a set of constraints.

Hence, from this review one can notice that there is a lot of interest in investigating climate change impact on economic and energy systems. However, although models are very detailed in their economic and technical parameters like growth rate and cost of technologies, lack of attention has been paid to adequate measure of investment attractiveness and/or time preference through de adequate choice of discount rates. Studies mentioned in the chapter 3 of this thesis, like Stern (2007) and Nordhaus (2007) used economic IAMs to evaluate economic losses under climate change restrictions and they discussed the discount rate issue, but literature lacks studies that evaluate how technology transition pathways under climate change policies may be affected by the choice of the discount rate.

Therefore, it makes sense the conception of a national level model to integrate the discount rate discussion with energy system modeling in order to evaluate impacts on the energy system and guide policy decision. This is because discount rates are in general discussed at a national level[35], just as climate and energy policies. Fais and Blesl (2015) affirm that the complexity of climate change policy in real world leads to a need of a highly

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[35] For instance, in the case of Brazil, the national long-term interest rate that marks out the financing of large investments is set by Brazil's Social and Economic Development National Bank (BNDES).

detailed model comprising a large range of technologies to reach a realistic depiction of the policy impact. Moreover, the technology rich framework enables the analyst to identify cost-effective mixes of technologies and to direct properly incentives to invest in specific areas of interest, but it is important to keep in mind that changes in discount rate parameter might lead to significant change in scenario results, modifying analyst's possible recommendations.

Furthermore, testing different discount rates under an integrated energy modeling approach allows identifying the difference between social and market point of view, helping to bridge the gap between public and private sector in the decision-making, once chosen the storyline to follow and the adequate way to promote sustainability.

Therefore, in this thesis an energy system model is developed and adopted to generate three sets of scenarios runs with different climate policy restrictions and different discount rates. The next sections of this chapter will describe the model to be adopted, the parameters and characteristics of TIMBRA (TIMES model adapted for Brazil), which is the developed Brazil's energy system model in the TIMES software platform.

4.2 Optimization Tool: the Integrated MARKAL-EFOM System (TIMES)

As explained before in the Introduction and in section 4.1, for the purpose of this thesis it will be adopted an integrated energy system model to evaluate Brazil's energy system under different climate policies and subject to different discount rates. This section details the tool adopted as an energy system model, its main characteristics and principles.

The model to be adopted in this thesis is The Integrated MARKAL-EFOM System, or just TIMES, a model developed and maintained by the Energy Technology System Analysis Programme (ETSAP), which is an implementing agreement under the International Energy Agency (Loulou & Labriet 2008). The authors say that TIMES is a successor of MARKAL (Fishbone and Abilock 1981; Fishbone et al. 1983; Berger et al. 1992) and EFOM (Finon 1974; van der Voort et al. 1984) bottom-up energy models and incorporates their features, such as the detailed description of technologies, detailed representation of energy flows and equilibrium properties, plus new ones. Some of these new features are: variable length periods, vintaged technologies, detailed representation of cash flows in the objective function, technologies with flexible inputs and outputs, stochastic programing with risk aversion, climate module and; endogenous trading between regions (Loulou & Labriet 2008).

As stated by Loulou et al. (2005), the TIMES model is an economic model generator for local and multi-regional energy systems and it provides a basis for estimating energy pathways over a long-term, multi-period time horizon. It may be applied to evaluate either an energy system as whole or a specific segment of it, like electricity or district heat sector.

Different end-use energy demands (final or useful) for sectors and regions are exogenous to the model as well as existing stock of available technologies and characteristics of technologies to be available in the future (efficiencies, investment and O&M costs, lifetime, etc). Available resources and resource potentials are also given to the model by the user (Loulou et al. 2005a).

Once these inputs are given, TIMES aims at supplying energy demands at minimum global cost or, more precisely, minimum loss of surplus. It simultaneously makes equipment investment and operating, primary energy supply and energy trade decisions by region. This means that the choice of equipment to be adopted by the model is based on its characteristics and characteristics of alternative equipment, on the economics of energy supply and on environmental criteria, when applied. Therefore, TIMES is considered to be a vertically integrated model of energy systems (Loulou et al. 2005a).

Loulou et al. (2005) say that TIMES may also represent materials and environmental emissions properly, opening the possibility to expand its scope beyond energy issues. Moreover, the authors also highlight that quantities and prices of commodities are in equilibrium, which means that suppliers produce exactly demanded quantities, leading to the maximization of the total surplus.

Being that explained, Loulou et al. (2005) say that TIMES is an adequate tool to explore energy futures based on scenario analysis that consist of energy demands, resource potentials, policy settings and a set of commodities and energy conversion technologies with proper description.

Remme et al. (2009) describe that TIMES is formulated as a linear programing problem under its standard formulation, which means that both constraints that describe the energy system, like efficiency or availability factor, and the objective function are of linear nature. Also, decision variables determined by the optimization, like capacity additions, are continuous and positive. The authors point out that there are variants of the model that may change the type of the optimization problem. However, they were not adopted in this thesis and, hence, will not be detailed.

Loulou (2008) states that a linear programming problem consists in the minimization (or maximization) of an objective function defined as a mathematical expression of decision variables, subject to constraints, also expressed mathematically. In the case of TIMES, the mathematical structure is formulated with GAMS® language and solved via IBM Cplex® solver. The author attempts to simply describe TIMES optimization program based on the three basic elements of linear programming: decision variables, objective function and constraints.

Decision variables are the endogenous quantities defined by the optimization. (Loulou 2008) lists TIMES' decision variable as follows[36]:

- NCAP(r, v, p): New capacity addition (investment) for technology p, in period v and region r.
- CAP(r,v,t,p): Installed capacity of process p, in region r and period t(optionally with vintage v).
- CAPT(r,t,p): Total installed capacity of technology p, in region r and period t.
- ACT(r,v,t,p,s): Activity level of technology p, in region r and period t (optionally vintage v and time-slice s).

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[36] Indexes adopted in the list are as follows: r-region, t-time period, v-vintage year (when vintage is on), p-process (technology), s-time slice, c-commodity.

- FLOW(r,v,t,p,c,s): The quantity of commodity c consumed or produced by process p, in region r and period t (optionally with vintage v and time-slice s).
- SIN(r,v,t,p,c,s)/SOUT(r,v,t,p,c,s): The quantity of commodity c stored or discharged by storage process p, in time-slice s, period t(optionally with vintage v), and region r.
- TRADE(r,t,p,c,s,imp) and TRADE(r,t,p,c,s,exp):) Quantity of commodity c (PJ per year) sold (exp) or purchased (imp) by region r through export (resp. import) process p in period t (optionally in time-slice s).
- D(r,t,d): Demand for end-use energy service d in region r and period t.
- Other variables: not strictly needed, but convenient. Examples: COMPRD (total amount produced of a commodity) or COMCON (otal amount consumed of a Commodity).

As Loulou (2008) discusses, TIMES computes for each region a total net present value of annual costs, discounted to the reference year and then aggregate these costs to a total cost, which constitutes the objective function to be minimized. Loulou (2008) gives a simplified version of this function as follows (Equation 4-1):

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST_{(r,y)}$$

(Equation 4-1)

Where:

NPV: the net present value of the total cost for all regions (the TIMES objective function);

$ANNCOST_{(r,y)}$: the total annual cost in region r and year y;

$d_{r,y}$: general discount rate

REFYR: reference year for discounting;

YEARS: set of years for which there are costs;

R: set of regions.

Loulou et al. (2005b) provide two equations with a better depiction of objective function's components which helps understand the role of system's cost elements listed before. As (Equation 4-2) express the objective function as the sum of regional optimization, (Equation 4-3) decomposes the regional objective function in nine components:

$$VAR\_OBJ(z) = \sum_{r \in REG} REG\_OBJ(z, r)$$

(Equation 4-2)

$$\begin{aligned} REG\_OBJ(z, r) = \sum_{y \in (-\infty, +\infty)} DISC_{(y,z)} * \\ * \{INVCOST(y) + INVTAXSUB(y) + INVDECOM(y) + FIXCOST(y) \\ + FIXTAXSUB(y) + VARCOST(y) + ELASTCOST(y) - LATEREVENUES(y)\} \\ - SALVAGE(z) \end{aligned}$$

(Equation 4-3)

Where:

y: year;

z: reference year;

r: region;

VAR_OBJ(z): total system cost discounted to reference year z;

REG_OBJ(z,r): system cost of region r discounted to reference year z;

DISC(y,z): Value, discounted to the beginning of year z, of a $1 payment made at beginning of year y, using general discount factor;

INVCOST(y): Parameter representing the investments portion of a regional component of the objective function;

INVTAXSUB(y): Parameter representing the taxes and subsidies attached to the investments portion of a regional component of the objective function;

INVDECOM(y): Parameter representing the capital cost attached to the dismantling (decommissioning) portion of a regional component of the objective function;

FIXCOST(y): Parameter representing the fixed annual costs portion of a regional component of the objective function;

FIXTAXSUB(y): Parameter representing the taxes and subsidies attached to fixed annual costs of a regional component of the objective function;

VARCOST(y): Parameter representing the variable annual cost portion of a regional component of the objective function;

ELASCOST(y): Variable representing the demand loss portion of a regional component of the objective function (elasticity effect);

LATEREVENUES(y): Parameter representing the late revenue portion of a regional component of the objective function;

SALVAGE(z): Parameter representing the salvage value portion of a regional component of the objective function.

The objective function detailed above is constrained by a set of equations that should express physical and logical relationships that should be satisfied in order to depict the energy system properly. Model will be unfeasible if at least one of these constraints are not satisfied. Loulou (2008) lists the most important types of constraints that should help model the energy system. They are: capacity transfer (conservation of investments); definition of process activity variables (boundaries to activity); use of capacity (boundaries to capacity expansion); commodity balance equation (coherence between inputs and outputs); flow relationships, among others. Absolute constraints might be an upper limit, a lower limit, or a fixed amount and share constraints are also possible.

Moreover, TIMES objective is to minimize the total cost of the system, as mentioned before, and all cost elements are properly discounted to a selected year. Although TIMES' variables (including constraints) are linked to a period, system's costs are expressed for each year of the horizon and includes the following elements (Loulou 2008):

- Capital or investment costs;
- Fixed and variable annual Operation and Maintenance (O&M) Costs;
- Import costs and export revenues;
- Delivery costs for required commodities consumed by processes;
- Taxes and subsidies associated with flows and activities;
- Revenues from recuperation of embedded commodities (accrued when a process's dismantling releases some valuable commodities);
- Salvage value of processes and embedded commodities at the end of the planning horizon;
- Welfare loss resulting from reduced end-use demands.

As a linear programing problem, TIMES' solution consists of two parts: the primal and the dual solution. Remme et al. (2009) explain that primal solution gives the optimal values of primal decision variables. Loulou & Labriet (2008) list primal solutions of TIMES for each time period and region: (i) set of investments in all technologies; (ii) the operating level of all technologies; (iii) the imports and exports of each type of tradeable energy forms and materials; (iv) the extraction levels of each primary energy form and materials; (v) the flows of each commodity into and out of each technology; (vi) the emissions of each substance per technology.

Meanwhile, the dual solution is related to marginal or opportunity costs assigned to each constraint of the primal problem (Remme et al. 2009). Loulou & Labriet (2008) list as dual solutions the shadow price of each commodity presented in the reference energy system and the reduced cost of each technology in the reference energy system[37]. Remme et al.

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[37] Reference energy system is the set of technologies, energy carriers and energy flows (link between commodities and carriers) that defines the structure of the model (Loulou et al. 2005b; Loulou & Labriet 2008).

(2009) give as example the CO_2 emission constraint, that has as its dual the CO_2 shadow price (the marginal cost of reducing one ton of CO_2).

Loulou & Labriet (2008) affirm that TIMES is defined by variables and equations determined by input data provided by the user. That input data is composed by quantitative and qualitative elements. Qualitative elements are those which define energy carriers, available technologies and environmental emissions to be tracked, while quantitative elements define the technological and economical parameters that characterize technologies per region and time period.

Time horizon may be divided into a user-chosen number of time periods and all years in a given period are considered identical. Year in a period are considered equal, except in light of the cost objective function, since it differentiates between payments in each year of a period and investment variables, as previously exposed. Also, except for investment variables, all quantities (capacities, flows, etc) are applied to each year of a period (Loulou & Labriet 2008).

The initial period is the base (or reference) year and, in general, it is a single year in the past that has to be properly calibrated in order to characterize the energy system and define from what conformation it will evolve. Loulou & Labriet (2008) point out the main variables to be calibrated: capacities and operating levels of technologies, extracted, exported, imported, produced and consumed quantities for energy carriers, besides emission factors.

Besides time-periods, it is also possible to divide time within a year through the establishment of time-slices by the user. It is possible to define seasons, day/night and weekdays and weekends. It is an important characteristic of the model, since there are energy carriers with different production and consumption profiles at different times of the year, such as intermittent sources of energy (wind and solar) and/or heating demand (Loulou & Labriet 2008).

Loulou & Labriet (2008) make an overview of the TIMES attributes. They show that process-oriented parameters are categorized in three levels:

- Technical parameters: which include efficiency, availability factor(s), commodity consumptions per unit of activity, shares of fuels per unit activity, technical life of the process, construction lead time, dismantling lead-time and duration, amounts of the commodities consumed (respectively released) by the construction (respectively dismantling) of one unit of the process, and contribution to the peak equation.
- Economic and policy parameters, such as costs attached to the investment, dismantling, maintenance, and operation of a process. It also includes taxes and subsidies, economic life of a process[38] and the process specific discount rate, also called hurdle rate.
- Bounds, which might be lower, upper or equal. These may be imposed on the investment, capacity or activity of a process.

The same authors (Loulou & Labriet 2008) mention that process parameters may be vintage, which means that they may depend upon the date of installation of new capacity, i.e., dependent on the age of the technology[39].

Regarding commodity parameters, they also fall into three categories (Loulou & Labriet 2008):

- Technical parameters, such as overall efficiency (expl: grid efficiency) and time-slices over which they are tracked. Also, annual projected demand and load curves, when commodities are specified as demands.

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[38] Which is the time during which the investment cost of a process is amortized, which may differ from the operational lifetime.

[39] To make it clearer, the authors give the example of the annual maintenance cost of an automobile: it could be defined to remain constant for three years and then increase linearly each year after the third year (Loulou and Labriet 2008).

- Economic parameters, such as additional costs, taxes, and subsidies on the production of a commodity. Also, price elasticity parameters may be specified for demand commodities if convenient.
- Policy based parameters, such as bounds on production, imports or exports of a commodity. Bound may be cumulative or per period.

Loulou & Labriet (2008) also list parameters attached to commodity flows, i.e., to the amount of inputs (consumption) and outputs (production) of a process. They are:

- Technical parameters that should control the maximum and minimum share of input or output flow may take within a group of commodities in or out a process.
- Economic parameters, such as delivery and other variable costs or any other cost, tax or subsidy linked to an individual process flow.

The same authors (Loulou & Labriet 2008) also highlight that there are parameters in TIMES model that regard the whole energy system, such as currency conversion factors (in a multi-regional model), region-specific time-slice definitions, region-specific values of capital and labor (influencing the costs of technologies), a region-specific general discount rate, and reference year for calculating the discounted total cost (objective function). Moreover, there are switches that control the activation of the data interpolation procedure as well as special model features to be employed.

There are also some aspects of TIMES' economic rationale that should be mentioned. TIMES is a technology explicit, multi-regional, partial equilibrium model that assumes price elastic demands[40], competitive markets and perfect foresight (Loulou & Labriet 2008). Regarding technology explicitness, it should be said that the model is data driven and that the richness in technology sets and descriptions depends on the user, not on model's equations. The latter remains the same across models. Also, it should be said that TIMES

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[40] If convenient to the user. In TIMBRA, this feature is not adopted.

allows different regions to be linked by trading properties, reflecting real markets worldwide or at a regional level.

Regarding partial equilibrium properties, TIMES assumes that input-to-output relationships are linear, meaning that technologies may be implemented at any capacity, continuously within the established bounds without economies of scale. This is what allows TIMES equilibrium to be computed using linear programing. However, it does not mean that production functions behave in a linear fashion, since these are usually non-linear (but convex), representing non-linear functions as a stepped sequence of linear functions (Loulou & Labriet 2008).

The other aspect of partial equilibrium property is the maximization of total surplus. Loulou & Labriet (2008) explain that the total surplus of an economy is the sum of suppliers' and consumer's surpluses and that also apply to TIMES. The supply curve of a given commodity is endogenous to the model and do not need to be explicitly specified. When it comes to demand curve, it is endogenous only if the commodity in question is an energy carrier whose production and consumption are also endogenous. Otherwise, the demand curve is exogenous and given by the user based on values for each period or on their own-price elasticities.

Moreover, TIMES assumes also competitive energy markets with perfect foresight, which means that market is assumed to have multiple agents with no market power and with perfect information. Perfect information incurs in complete knowledge about market parameters, present and future. This entails the standard consequence that market price of a commodity is equal to its marginal value, as says microeconomic theory (Loulou & Labriet 2008). However, it is possible for the user to limit foresight assumption over one or a few periods of the time horizon and this feature was adopted in some scenarios generated in this thesis.

Once TIMES rationale was exposed, the next section details how it was modeled in order to reflect Brazil's energy system subject to climate policies and discount rates. Premises on discount rates, on policies to be tested and sets of processes and commodities adopted are depicted in the next section.

4.3 Modeling Aspects

Brazil's energy system modeled under TIMES framework was named TIMBRA, an acronym for TIMES-BRAZIL. TIMBRA is the first version of Brazil's entire energy system in TIMES and its structure was based on MESSAGE-Brazil[41], which is the model commonly adopted by UFRJ's Energy Planning Program to make integrated studies related to Brazil's energy system. The most recent studies available in the literature where MESSAGE-Brazil was used, as mentioned in section 4.1, are Oliveira et al. (2016) Herreras Martínez et al. (2015), Lucena et al. (2015) and Nogueira et al. (2014).

In this section, the main structure and premises adopted for TIMBRA will be described.

4.3.1 Structure of Brazil's Energy System in TIMBRA

As explained previously, an energy system is described in TIMES framework through a set of processes (or technologies) that "carries" energy flows along different energy levels of an energy chain. Under this scheme, energy resources are transformed in final and useful energy types that supply the energy demands given by the user.

The time period considered is from 2010 to 2050, being 2010 the base year, i.e., the calibrated year in the model. Time horizon is divided in 5-year time periods and time slices divide a 24-hour day in five parts[42], according to the structure developed by Borba (2012). Daily oscillations of load and generation (for intermittent energy sources) are distributed along these time slices.

Moreover, for the Brazilian case, it was established a set of five main energy levels and within each level lies different energy forms as energy commodities. These commodities depend on resources and generating technologies. Figure 4-1 below describes in a concise way the set of processes and commodities that represent Brazil's energy matrix within

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[41] The version used for TIMBRA was mainly based on (Oliveira et al. 2016).

[42] 0-6 hours; 6-10 hours; 10-18 hours; 18-21 hours; 21-24 hours.

TIMES model. The vertical lines are energy commodities and the boxes are the available energy conversion processes. The horizontal lines indicate the commodities that serve as inputs and outputs of the different processes. It is worth noting, though, that since it is a summary of TIMBRA, the figure omits auxiliary energy levels and processes that were used to give a better depiction of the system for the model. These auxiliary inputs are tools that lead to a better operationalization of TIMBRA towards the complexities of Brazil's energy system. However, Figure 4-1 gives an adequate and sufficient description as it is in TIMBRA.

From this structure, the linear programming model is forced to solve a matrix of 39.740 rows and 48.244 columns[43] when optimizing in order to minimize the objective function.

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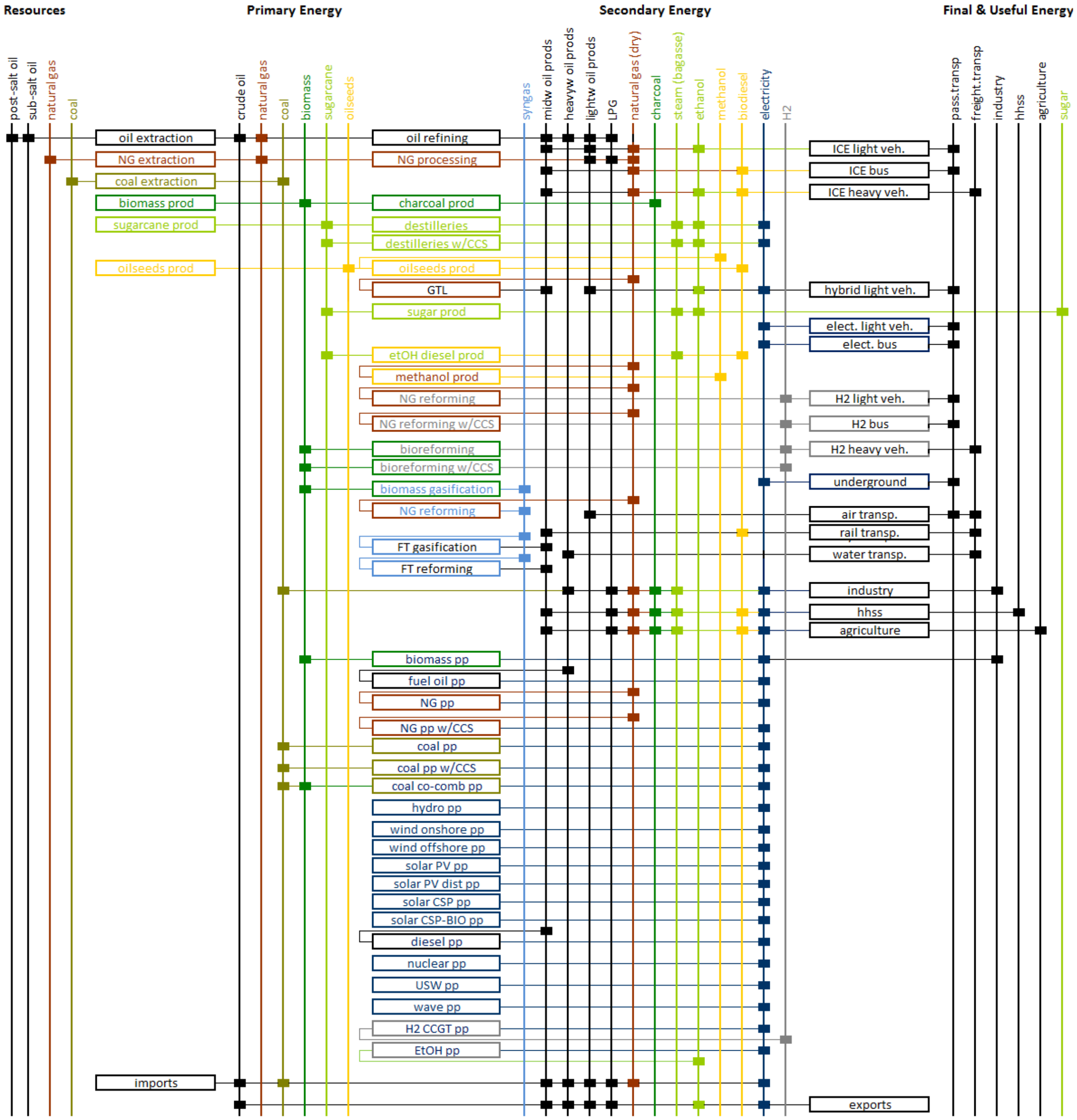
[43] Exact number may vary from one scenario run to another.



Glossary:
prod: production
GTL: gas-to-liquids
pp: power plants / plantas de geração
midw oil prods: medium-weight oil products (diesel)
heavyw oil prods: heavy-weight oil product (fuel oil)
lightw oil prods: light-weight oil products (gasoline, jetfuel)
LPG: liquefied petroleum gas
USW: urban solid waste
NG: natural gas
FT: Fischer-Tropsch
CSP: concentrated solar power
PV: photovoltaics
veh: vehicles
hhss: household and services
CCS: Carbon Capture and Storage
CCGT: Combined Cycle Gas Turbine
EtOH: ethanol

Figure 4-1 – Simplified structure of TIMBRA.

Source: Adapted from Borba et al. (2012).

It should be mentioned that regarding electricity generation, Brazil is divided in 3 sub-regions in TIMBRA in order to reflect the interconnections of south, middle west and southeast regions (subsystem S1), the interconnections of North and Northeast regions (subsystem S2) and the isolated system (subsystem R). Possible electricity interchanges between these regions are also duly expressed in the model. Therefore, energy flows from generation centers to final consumers within the regions and long-distance transmission capacities are properly described in TIMBRA.

4.3.1.1 Energy Levels

Brazilian energy system in TIMBRA may be divided in five main energy levels plus two dummy levels that are auxiliary to the energy system. This division is not as explicit in the model as it is in MESSAGE-Brazil (Borba 2012, Nogueira, et al. 2014, Schaeffer et al. 2014), but it is still useful to understand the structure of the energy system.

- Resources: in TIMBRA, extraction limit of resources is given by the conversion efficiency of processes that convert them to primary energy. For renewable resources (like solar and wind, for example), there is no need to declare extraction constraints. Four exhaustible resources are considered: coal, non-associated natural gas, crude oil from post-salt layer and crude-oil from sub-salt layer[44].
- Primary energy: it includes resources available after extraction like: crude-oil, associated and non-associated[45] natural gas after extraction, coal after extraction, biomass, sugarcane and oilseeds after harvest. Primary energy sources should go to conversion and processing units, like refineries, NGPU and distilleries, in order to be converted into secondary sources of energy.
- Secondary energy: this energy level contains energy flows from conversion and treatments units of primary or secondary energy[46]. The energy commodities that fit into this category are: oil products from refineries[47], processed and dry natural gas from NGPU (natural gas processing units),

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[44] Produces, at primary level, associated natural gas.

[45] Including shale gas.

[46] It is possible to convert a secondary energy source into another secondary energy source. An example is the conversion of natural gas into syngas.

[47] The model considers: light oil products – gasoline and jetfuel; medium oil products – diesel; heavy oil products – fuel oil and coke from oil; liquefied petroleum gas – LPG; and non-energy oil products – petrochemical naphtha.

syngas from natural gas reforming and biomass gasification, charcoal from biomass, ethanol and sugarcane bagasse from distilleries, ethanol from sugarcane bagasse hydrolysis, methanol[48] from natural gas, biodiesel from oilseeds and electricity generated in different types of power plants in subsystems S1, S2 and R.

- Final energy: it includes all energy commodities that may be directed to final consumption, becoming useful energy. Therefore, secondary energy sources that were already transmitted, distributed or blended, i.e., are ready for consumption, fit into this category. Final energy commodities are: oil products under consumption legislation composition (with the proper blend with biofuels, for example), consumption-ready dry natural gas, national and imported coke, biomass[49], charcoal, sugarcane bagasse, ethanol, biodiesel and electricity distributed in subsystems S1, S2 and R.
- Useful energy: this is the last energy level considered in the model. Within this level exogenous demands are allocated. Hence, technologies before this level convert final in useful energy according to given efficiencies (like efficiencies of vehicle engines, of lamps at households, etc). Energy forms considered at this level are: driving force in vehicles (i.e., burning fuel in gasoline, ethanol, flexfuel, diesel and electric vehicles; feedstocks (that should reflect production and consumption of non-energy products along energy chains in the system); electricity[50] in subsystems S1, S2 and R; and thermal energy in eleven industrial sectors[51], agriculture and edifications (household and services).
- Dummy energy: the adoption of dummy levels of energy aims at disaggregating conversion technologies that adopt more than one production

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[48] Methanol is considered a secondary source for biodiesel production.

[49] In this case, biomass at final energy level is the primary biomass directed to power generation in some industrial sectors.

[50] Useful energy consumption of electricity reflects the whole aggregated electricity demand of the energy system, i.e., includes all economic sectors.

[51] Eleven industrial sectors are considered: mining, cement, ceramics, pulp and paper, steel, iron and nickel, iron-alloys, chemical, food and beverages, textile and others.

step and that may possibly suffer retrofits[52]. This is the case of the natural gas that has to go to NGPUs before going to consuming units (power plants, refineries[53], etc). Another example is the final production of diesel that should generate a fuel with 5% biodiesel content. Besides, dummy energy levels are adopted in order to duly reflect the transportation and distribution of electricity within the energy system, as well as electricity interchanges between subsystems.

4.3.1.2 Primary Energy Production Processes

Primary energy production technologies convert resources in primary energy once considered losses in extraction and processing. Three sets of processes are considered in TIMBRA: oil and natural gas extraction, coal extraction and extraction and harvesting of renewable sources.

i. Oil and Gas Exploitation

TIMBRA considers separately oil and wet natural gas extraction from post-salt and sub-salt layers. The amount of wet natural gas extracted from oil platforms is quantified based on an oil-gas ratio exogenous to the model and obtained from ANP (2012). There are minimum and maximum oil extraction limits defined per each period in the time horizon. This limit follows a multi-Hubbert curve based on Saraiva et al. (2014). Oil prices were based on a robustness price[54] of US$ 50/barrel of Brent oil.

Non-associated natural gas extraction is based on resource estimates according to ANP (2012). Either for non-associated or associated natural gas, a 10% loss in extraction and

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[52] Such as CCS in thermal power plants.

[53] Including the hydrogen generation unit for oil hydrotreatment step in refineries.

[54] Brent (international oil price marker) robustness price is defined as the minimum price that should make viable oil exploitation and production projects in Brazil.

transportation to UNPGs are accounted. Natural gas prices were adopted in accordance to ANP (2010) and Sienem and Pedras (2011).

Besides conversion units that reflect extraction technologies, TIMBRA also considers conversion units that reflect oil and gas imports and exports. It is adopted the premise that oil import costs are higher than extraction costs due to the better quality of the imported oil. Natural gas might be imported through gas pipelines, reflecting imports through Brazil-Bolívia pipeline, or as liquefied natural gas (LNG).

ii. Coal Extraction

Coal extraction in the South region of Brazil is considered and coal extracted is assumed to have a worse quality than imported coal. Coal extraction efficiency and costs are in line with Nogueira et al. (2014) and Borba (2012). Thermal coal, metallurgical coal and coke imports are also in line with Nogueira et al. (2014) and Borba (2012).

iii. Renewable resources production

The model considers three types of renewable sources for biofuels: sugarcane for ethanol production, oilseeds for biodiesel production and biomass for the production of charcoal and firewood. No activity constraint was considered since these are renewable resources and production costs are not considered in this upstream part of the energy chain because there is a fixed demand for biofuel products[55].

4.3.1.3 Secondary Energy Production Processes

Secondary energy is obtained from proper treatment and conversion of primary or other secondary energy sources. It constitutes one step towards the production of final energy levels that should comply with regulatory and technologic specifications.

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[55] This reflects the mandatory 5% to 7% level of biodiesel in final diesel and the mandatory 20% to 27% level of ethanol in final gasoline (in a volume basis).

TIMBRA considers three sets of conversion technologies within this category: oil refineries and NPGUs, first and second generation biofuels production processes, power plants from different energy sources.

i. Oil Refineries, Natural Gas Processing Units and Advanced Technologies

Regarding refining, it was considered four refining groups. The first group refers to existing refineries. Data related to crude processing and oil products conversion rates were obtained based on ANP (2013). It was also considered a self-consumption rate of 8% in this group of refineries.

The other three blocks of refineries consider units in construction or under evaluation by Petrobras. The second refining group has RNEST[56] characteristics, a refinery to be located in Pernambuco and expected to full start-up in 2020. The third refining group has COMPERJ[57] characteristics, which is expected to start-up in 2017 in Rio de Janeiro with focus on diesel production. Finally, the fourth refining group has Premium refineries characteristics: these were supposed to start-up in 2020, but had their projects cancelled in the beginning of 2015. However, in TIMBRA, this refining group was maintained as an option to expand refining in Brazil, if needed, with a new addition limit of 200,000 barrels per day (bpd) at a US$ 50,000.00/bpd investment level (Barros 2014).

TIMBRA also considers imports and exports of oil products in order to reflect Petrobras behavior: it imports better quality diesel and gasoline to cope with national environmental legislations, and it exports fuel oil at reduced prices. The import limit was based on Barros (2014), which estimated Brazil's maximum ports capacities for receiving light and medium imported oil products. It should be mentioned, however, that the model was free to export oil products in the long term, which may generate results that reflect model adjustments to fulfil given demands and do not necessarily reflect real behavior of Petrobras.

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[56] Refinaria Abreu e Lima.

[57] Complexo Petroquímico do Estado do Rio de Janeiro.

Regarding NGPUs, TIMBRA considers only one type of conversion technology to reflect them according to Brazil's NGPUs profile. NGPUs are considered to be near natural gas extraction platforms and they are always similar, having, hence, the same cost and efficiency. Data regarding NGPUs are in accordance to Borba (2012).

ii. Biofuels Production

In Brazil, most relevant biofuels are ethanol from sugarcane and biodiesel from soybeans. It is considered the first generation ethanol production, from simple sugarcane fermentation in distilleries. It is also considered second-generation ethanol production from biochemical and thermochemical hydrolysis and possibilities of cogeneration with CEST[58] and BIG-CCGT[59] turbine technologies. Parameters adopted for these conversion processes were in accordance with Schaeffer et al (2014), Walter & Ensinas (2010), Ensinas et al. (2007), Palacios-Bereche et al. (2013), Seabra & Macedo (2011) and Seabra et al. (2010).

Technology conversion of oilseeds into biodiesel is also considered and it has as secondary input methanol from natural gas, which is necessary to the transesterification process.

iii. Advanced Fuels

Besides the conventional production of oil products in refineries and of dry natural gas in NGPUs, the model may also produce, in the mid to long term (after 2020), medium hydrocarbons, i.e., diesel through Fischer-Tropsch reaction. The syngas used for this may be obtained through natural gas reforming or through biomass gasification (gas-to-liquids and biomass-to-liquids technologies, respectively). Quantitative input data is in accordance to

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[58] Condensing-extraction steam turbine.

[59] Biomass integrated gasification with combined cycle gas turbines.

Schaeffer et al. (2014). It is also considered the possibility of obtaining diesel from sugarcane juice[60] and H-bio[61] according to parameters of Borba (2012).

Moreover, scenarios considering the adoption of Hydrogen vector as fuel in transport sector (through the adoption of fuel cell vehicles) include a natural gas reforming unit after NGPUs in order to generate H_2. Likewise, when hydrogen usage in the transport sector is considered, it is also added a biomass gasification unit after biomass treatment in order to generate H_2 to this end (Schaeffer et al. 2014; Lindsay et al. 2009).

iv. Electricity Generation (Fossil and Renewable)

Due to the diversity of available resources, Brazil has different types of power plants and the hydropower is the predominant type. Therefore, it was considered three types of hydroelectric generation in the three subsystems of Brazil: large hydropower plants, with capacities above 300 MW; medium hydropower plants, with capacities between 300 MW and 30 MW and; small hydropower plants, with generation capacities below 30MW. Installed existing and to be expanded capacity is in accordance with de Lucena et al. (2010) and with Generation Information Database from ANEEL (ANEEL, 2014) in order to reflect new projects and projects under construction properly in the model.

When it comes to thermal power generation, it was considered the existing pulverized coal power plants with possibility of expansion of this technology. It was also considered the possibility of installing integrated gasification combined cycle (IGCC) power plants from 2020 on. Input data (capacities, efficiencies, availability factors, capital costs, etc) were included in accordance with Rochedo (2011) and Nogueira et al. (2014).

It is worth noticing that pulverized coal power plants in subsystem S1 adopts as feedstock the national coal produced in the south region of Brazil. It was also added the

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[60] This process adopts genetically modified yeast that converts sugarcane juice into up to fifteen-carbon chain chemical products (Amyris 2010). The diesel obtained in this process is free from impurities like sulfur, which is limited by environmental legislation.

[61] H-Bio is the processing of vegetable oil mixed directly with diesel via HDO/Hydrodeoxigenation (Borba 2012).

possibility of mixing national coal with biomass in a co-firing technology. With a limit of 30% of biomass as feedstock. Data regarding biomass treatment and input in the thermal power plants is in accordance with Hoffmann (2013).

Regarding natural gas power generation, it was considered open cycle and combined cycle power plants in the three subregions and it was adopted as a premise the fact that expansion would happen by the adoption of combined cycle power plants. Efficiencies, costs and other relevant data were added in accordance with Borba (2012), Rochedo (2011) and Nogueira et al. (2014). Moreover, it is also considered in TIMBRA the possibility of adoption of flexible CCGT technologies in S1 and S2 in accordance with Soria et al., (2015a) in order to make it available a flexible technology to cope with the adoption of intermittent energy sources.

When it comes to renewable generation, Brazilian energy system includes wind and solar (both photovoltaics and concentrated solar power) generation, plus sugarcane bagasse electric cogeneration at ethanol distilleries and urban solid waste.

Regarding wind energy, it was considered only in S1 and S2 subsystems, given available technical potential. Existing and planned wind farms were included according to (ANEEL, 2014) and it was given the option to expand this source within its technical potential as of Amarante et al. (2001). Cost data are in accordance with Borba (2012) and IRENA (2012) and it should be mentioned that from the first author it was taken seasonality parameters that were estimated based on NASA (2010). Offshore wind generation was also given as an option to TIMBRA based on technical potential given by Ortiz and Kampell (2011) and economic data given by IRENA (2012).

When it comes to solar generation, photovoltaic technology was considered as centralized generation and distribution generation. Technical and economic data were adopted in accordance with (Malagueta et al. 2013) for centralized PV and Miranda (2013) for distributed PV. Concentrated solar power was considered with different levels of storage in S1 and it was also considered a hybridized unit of CSP with biomass. Data for CSP was mainly based on Malagueta et al. (2013) and Soria et al. (2015b).

Sugarcane bagasse electricity generation was considered as a subproduct in ethanol production in order to reflect cogeneration units at distilleries that can export electricity to the grid. Four generating technologies were considered, according to Schaeffer et al. (2014): counter-pressure turbines at 22 bar, which is the most widely adopted technology currently in Brazil; condensing-extraction steam turbines (CEST), which is considered as an update to more modern turbines at existing units or as new units; and the biomass integrated gasification technology (BIG-CCGT) coupled to a gas turbine. This last technology is still economically unavailable today, so it is available to the model only from 2020. Technical and economic data was based on Walter & Ensinas (2010); Ensinas et al. (2007) and; Seabra & Macedo (2011).

Last, TIMBRA also considers electricity generation from urban solid waste biogas with input data in accordance with Borba (2012).

4.3.1.4 Secondary to Final Energy Conversion Technologies

Technologies described in this section constitute the final part of described energy flows and they reflect the proper distribution and conversion of energy sources in order to meet demands exogenously given to the model. Conversion technologies that transform secondary energy in final energy may reflect energy transmission and distribution, as well as processing of some commodities in order to cope with current legislation before delivery to final consumers. Moreover, conversion technologies that transform final energy in useful energy reflect final conversion technologies with respective efficiencies to generate energy services, like driving force, illumination, heating, etc.

i. Transport Sector

Final energy commodities that should be delivered to final consumer in the transport sector are the oil products and biofuels under legal specifications, natural gas and, for advanced technologies, electricity and hydrogen. Therefore, besides distribution processes, TIMBRA also considers blending technologies of oil products and biofuels, when applicable, so final fuels would cope with mandatory biofuel content targets. Moreover, these technologies allow a 5% to 7% biodiesel content in final biodiesel and a 20% to 27% hydrated ethanol content in final gasoline.

Regarding final to useful energy conversion technologies, the model includes all typical passenger and freight vehicles, i.e., internal combustion engine vehicles plus advanced vehicles to be available from 2020, like fuel cell vehicles, hybrid vehicles and electric vehicles. Input technical and economic data was adopted in accordance with Schaeffer et al. (2014), based on NREL (2013) and Ramea et al. (2013).

In summary, vehicles considered in TIMBRA are: ICE (internal combustion engines) vehicles for public transport (diesel and natural gas buses), for private transport (light gasoline C, ethanol, natural gas and flex vehicles), and for freight (natural gas, diesel, ethanol and hybrid heavy vehicles). It was also considered hybrid plug-in light private vehicles (they may use electricity, gasoline or ethanol as fuel), pure electric light private vehicles, hydrogen fuel cell vehicles for private and public transport and freight. Moreover, the model also includes transport on rail (train and underground) and air freight and passenger transport (using oil products).

Demands for the transport sector are given in transport service, i.e., passenger-km (pkm) or tonne-km (tkm) for passenger and freight transport, respectively. This way, model can choose, once respecting scrapping and penetration constraints of new vehicles and new modals, the least cost options for freight and passenger transport.

ii. Electric sector

Regarding electric sector, TIMBRA includes, from secondary level, costs and losses for transmission and distribution through SIN and the isolated system and also considers interchanges between subsystems.

As mentioned, the national grid within TIMBRA was disaggregated in three subsystems: S1, representing South, South-east and Middle-west regions, S2, representing North and Northeast and the isolated subsystem R. However, in accordance with Borba

(2012), the possibility of connection of R subsystem with the national grid was given to the model and planned to start in 2015, as expected. Other flows of electricity in TIMBRA are summarized in Figure 4-2.

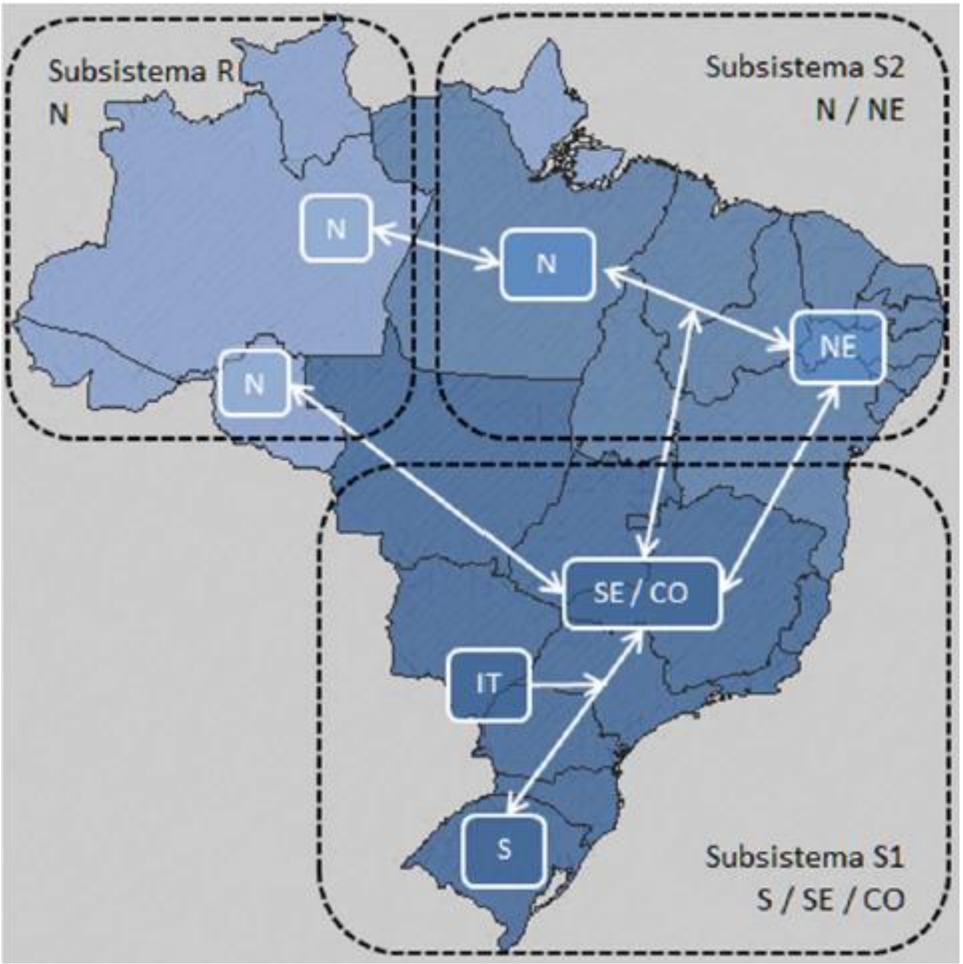

Figure 4-2 – Subsystems and electric interchanges in TIMBRA. (Note: N – North; S – South, SE – Southeast, NE – Northeast, CO – Middle-west, IT – Itaipu)

Source: Borba (2012).

Therefore, electricity commodity reaches the final level and is directed from final to useful energy conversion technologies in different economic sectors, such as the energy sector itself, transport sector (in case electric vehicles are adopted), industrial and buildings[62].

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[62] For industrial and edifications, it is considered the thermal demand for electricity. The rest of electricity use is aggregated as one electricity demand per subsystem.

In each sector, conversion efficiencies are considered in accordance with Schaeffer et al. (2014), Rathmann (2012), Borba (2012) and Lucena et al. (2010).

4.3.1.5 Final to Useful Energy: Industrial, agriculture and buildings sectors

Useful energy considered in industrial, agriculture and buildings (household and services) corresponds to the thermal energy demand and captive electricity in these sectors. Moreover, all fuels used in these sectors are led from secondary level to final level and then they are distributed in the system to final consumers under mandatory specifications. Final to useful conversion technologies are distinct per sector with different efficiencies, captive[63] consumption levels (when applicable) and operating and maintenance costs. Fuel costs are formed along the energy chain and, thus, they are endogenous to the model.

Agriculture and buildings sectors are not divided in subsectors and input data applies to the whole segment. On the other hand, industrial sector was divided in eleven subsectors that differ significantly in terms of production process and energy consumption. They are: mining, cement, ceramics, pulp and paper, pig iron and steel, non-ferrous metals, iron alloys, chemical, food and beverages, textile and other industries.

4.3.1.6 Carbon Emissions and Carbon Capture and Storage

In TIMBRA, CO_2 emissions are accounted in the Brazilian energy system. It is possible to distinguish energy CO_2 emissions (from burning fuels) and process CO_2 emissions (from a specific production process) by the way emission factors are given to the model. Energy emissions are accounted by declaring an emission factor associated with the fossil fuel in a specific emission factor spreadsheet. Moreover, process emissions may be input as one of the attributes of a specific technology, like oil refining or coal mining. Emission factors are multiplied by technology activities (for instance, fossil fuels emission factors are multiplied by fuel consumption and process emission factors are multiplied by the

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[63] Captive consumption is the amount of energy consumption (commonly from one specific energy source) that is fixed due to technological constraints of the energy conversion process.

production of the main product) in order to obtain total emissions of an energy conversion process.

For coal and natural gas thermal power generation (except for the open cycle technology option), carbon capture and storage was considered as a possibility after 2020, when the technology is supposed to become viable. In the case of coal, retrofits are allowed in existing pulverized coal power plant units and it is also possible to install capture-ready new units. Capture-ready IGCC power plants are also an option for the system after 2020. When it comes to natural gas-fired power generation, the retrofit of combined cycle units has high upfront cost and, hence, it was not considered. Instead, this technology can expand through the adoption of capture-ready new combined cycle units, in accordance with (Rubin et al. 2007).

It was also added to TIMBRA a bioCCS option, which is the capture of CO_2 from the fermentation process to generate ethanol. This results in negative emissions since emissions from the biomass lifecycle are not considered. BioCCS also was added on biomass gasification units for hydrogen generation. Similarly, regarding hydrogen generation, CCS option was also added in natural gas reforming step.

4.3.1.7 Energy Demands

This section presents the basic macroeconomic premises adopted to estimate energy demands and estimation results. Results and conclusions of scenario runs are strongly correlated to premises here presented, since the final objective is to meet demands given to the model and these may vary significantly depending on assumptions of economic growth. In order to estimate demands, two main indicators were adopted and projected to the long term horizon: gross domestic product and population.

i. Gross Domestic Product

Premises of future evolution of economic activities were based on the World Energy Outlook (WEO) from the International Energy Agency (IEA 2013). It was assumed that Brazil would grow at WEO's rates until 2035, which is the time horizon considered in this reference. After 2035, it was considered that Brazilian economic growth would converge to world growth rates projected for the period between 2021 and 2035, as it can be seen in Table 4-1. It is worth observing, though, that recent trends and the current conjuncture context in Brazil have dislocated its economic pathway from IEA (2013) projections, as discussed in chapter 2. In that sense, it is worth mentioning that absolute values obtained for this thesis are not as important as relative values across scenarios which will lead to an useful comparison. Moreover, the long-term nature of this analysis also reduces the impact of such short-term conjuncture. Hence, the fact that the adopted indicator does not reflect exactly current trend should not influence dramatically the outcomes of this thesis.

Table 4-1 – Premises for GDP until 2050.

	2010-2020	**2021-2305**	**2036-2050**
	(%p.y.)	**(%p.y.)**	**(%p.y.)**
Brazil	4.1	3.6	3.1
BRICS	8.0	4.4	-
World	4.0	2.9	-

*projection based on the convergence to world economic growth rates.

Source: based on IEA (2013).

It should be noted that all scenarios ran in TIMBRA adopted the same premises of economic growth. On one side, this is a weakness of energy systems models that are not able to evaluate possible feedbacks of climate policies on economic activity. This type of analysis, indeed, may be done with computable general equilibrium models (CGE). CGE models, however, do not allow a detailed evaluation of the energy sector either on the supply side (since technology representation is limited) or on the demand side (because they adopt price elasticities to reflect demands without more elaborated technical considerations).

On the other side, an exogenous scenario of macroeconomic growth allows models like TIMES to evaluate the feasibility of a specific level of development for the energy sector.

In other words, it is possible to test if energy resources and available technologies can cope with a given economic development.

ii. Population

Population premises have major influence in demand projections for the edifications and for the transport sector. It was considered as reference for 2050 the IBGE (2013) projections and these projections are consistent with intermediary scenario for Brazil elaborated by the World Bank. The Figure 4-3 below shows the projected evolution of population in Brazil adopted in TIMBRA. According the projection, Brazilian population would reach a peak of 220 million inhabitants around 2040 and then it would decrease to 215 million inhabitants in 2050.

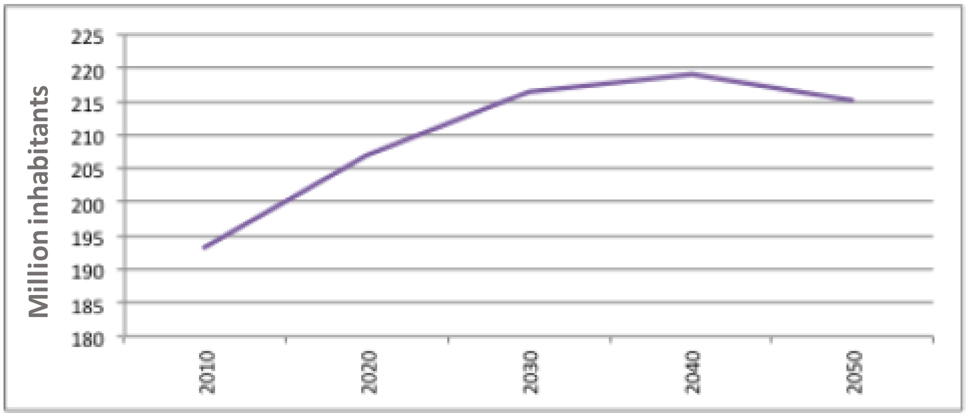


Figure 4-3 – Premises for population until 2050.

Source: IBGE (2013).

iii. Useful Energy Demands

As explained before, TIMES model optimizes an energy technology mix in order so supply a set of exogenous demands. These demands result from technical-parametric sectorial models that projects demands until 2050 based on premises of economic growth as presented previously based on Schaeffer et al. (2014). Input demands correspond to useful energy except for captive electricity demand, i.e., energy services that can be supplied only by electricity (for instance, appliances, illumination, electric motors, etc). The detailed demands per period and per sector are listed in Table 4-2.

Table 4-2 – Useful and final (captive electricity) energy demands in TIMBRA.

Demands	Unit	Final/Useful	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coke	ktoe	Final	7,651	11,593	13,237	14,933	16,841	19,057	21,549	22,580	25,579
Electricity (isolated system	TWh	Final	4	4	4	4	4	4	4	4	4
Electricity (S/SE/CO)[1]	TWh	Final	307	307	307	307	307	307	307	307	307
Electricity (N/NE)[1]	TWh	Final	83	83	83	83	83	83	83	83	83
Feedstock[2]	ktoe	Final	8,210	8,210	8,210	8,210	8,210	8,210	8,210	8,210	8,210
Transport (passenger)	pkm	Useful	1,156,115	1,156,115	1,156,115	1,156,115	1,156,115	1,156,115	1,156,115	1,156,115	1,156,115
Transport (freight)	tkm	Useful	1,549,975	1,549,975	1,549,975	1,549,975	1,549,975	1,549,975	1,549,975	1,549,975	1,549,975
Motors (others)[3]	ktoe	Useful	375	375	375	375	375	375	375	375	375
Sugar	kton	Final	31,779	31,779	31,779	31,779	31,779	31,779	31,779	31,779	31,779
Agriculture	ktoe	Useful	1,636	1,636	1,636	1,636	1,636	1,636	1,636	1,636	1,636
Edifications (thermal)	ktoe	Useful	18,466	18,466	18,466	18,466	18,466	18,466	18,466	18,466	18,466
Food and Bev. (thermal)	ktoe	Useful	16,518	16,518	16,518	16,518	16,518	16,518	16,518	16,518	16,518
Ceramics (thermal)	ktoe	Useful	1,978	1,978	1,978	1,978	1,978	1,978	1,978	1,978	1,978
Cement (thermal)	ktoe	Useful	1,686	1,686	1,686	1,686	1,686	1,686	1,686	1,686	1,686
Mining (thermal)	ktoe	Useful	949	949	949	949	949	949	949	949	949
Iron (thermal)	ktoe	Useful	3,765	3,765	3,765	3,765	3,765	3,765	3,765	3,765	3,765
Iron Alloys (thermal)	ktoe	Useful	911	911	911	911	911	911	911	911	911
Non-ferrous (thermal)	ktoe	Useful	2,197	2,197	2,197	2,197	2,197	2,197	2,197	2,197	2,197
Other industries (thermal)	ktoe	Useful	2,295	2,295	2,295	2,295	2,295	2,295	2,295	2,295	2,295
Pulp and Paper (thermal)	ktoe	Useful	6,645	6,645	6,645	6,645	6,645	6,645	6,645	6,645	6,645
Chemical (thermal)	ktoe	Useful	4,122	4,122	4,122	4,122	4,122	4,122	4,122	4,122	4,122
Textile (thermal)	ktoe	Useful	444	444	444	444	444	444	444	444	444

[1] Excludes electricity for thermal use in industry.

[2] Non-energetic uses.

[3] Motor not adopted in transport.

4.4 Scenarios Description

This section will explain the choice of the set of scenarios to be considered in this thesis, discussing the main premises and defining their nomenclature. First, the rationale of scenario choice is introduced by defining what are the base cases and what are the alternative scenarios. Secondly, discount rate choice for each approach is justified and the values for the discount rates adopted in each case are presented. Next, the premises of low carbon policies and other timing issues to be considered in alternative scenarios are presented and discussed. Finally, the set of scenarios to be run in TIMBRA are consolidated.

4.4.1 Scenarios Introduction: base cases and alternative scenarios

As stated by Clarke et al. (2014), baseline scenarios are the ones with projections resulting from no explicit action related to climate change mitigation. The baseline scenario works like a counterfactual scenario and it establishes a reference point for measuring the extent and nature of the required mitigation for a climate goal.

It is acknowledged that a reference scenario should reflect how most of energy projects are evaluated by agents, which leads to a descriptive approach in which projects are discounted with discount rates reflecting market perspective and different levels of access to capital of different sectors of the economy. In that context, the reference case is the one without low carbon policies and with distinct discount rates for each sector, reflecting descriptive representations of individual time preference. This will be the main baseline scenario among all base cases adopted in this work.

Moreover, since discount rate choice might be an indirect indicator of policy-making, this thesis also seeks to adopt three perspectives of discounting and to evaluate how these perspectives are reflected in Brazil’s energy system. Other perspectives reflected in discount rate choice other than the market/descriptive approach – social discount rate and declining discount rates – are considered secondary “base case” scenarios to be compared to market discount rates, the main baseline scenario.

Furthermore, a scenario in which a climate policy is put into effect is considered as ‘alternative’ to the baseline scenario. The alternative scenarios include also other timing issues aside the discount rate reflected on technological lock-in and delayed action regarding mitigation.

Therefore, low carbon policies to be tested (and the other timing issues, such as lock-in and delayed action, implied in their premises) will be applied to all three cases in order to assess Brazil’s technology mix under different discount rate approaches and to verify if discount rate choice may affect energy system’s evolution across low carbon scenarios. In the next sections it will be detailed how discount rates were selected to represent the three presented perspectives.

4.4.2 Discount Rate Choice

Three discount rates approaches are adopted in TIMBRA, generating three base cases and three sets of alternative scenarios. These three discount rate “base case” scenarios intend to reflect the same energy system under different perspectives: the first one is the market perspective, which considers the opportunity cost to invest and the risks perceived by private agents; the second perspective reflects the conventional social perspective in which market failures are not considered, i.e., the discount rate reflects the benefits to society as a whole; the last perspective attempts to integrate both approaches and to deal with the intergenerational issue by adopting a declining discount rate.

4.4.2.1 Market Discount Rate

Kolstad et al. (2014) explain that a descriptive approach is based on how individuals and markets make intertemporal financial decisions, which is reflected by market interest rates. The same authors point arguments and drawbacks to adopting descriptive discount rates. As an argument, they point that if capital from a safe and marginal project (whose return is equal to the interest rate) is reallocated to a safe project with same maturity, but returns smaller than interest rates, then the net impact is null to present generations, but negative to future generations. Therefore, in these situations, the discount rate should be equal to the shadow cost of capital. As a drawback, Kolstad et al. (2014) point that markets may not aggregate efficiently when some agents are not able to trade, which is the case of future generations. Moreover, interest rates tend to be driven by the impatient attitude of consumers towards transferring their own consumption to the future, which confronts climate change mitigation rationale, which is transferring consumption across different people and generations. This lead to the conclusion that defining discount rates is a normative problem.

For the purpose of this thesis, market discount rates were adopted in order to verify how Brazil’s energy system will cope with climate policies based on the perception of market agents and to compare with other perspectives of discount rate choice. Sectorial discount rates were adopted for different economic sectors, since it is expected that different sectors will have different levels of access to capital, different perceptions of risk and different types and levels of market failures.

Hence, twenty different market discount rates were adopted, as listed in Table 4-3 and allocated to processes within each sector. These discount rates were based on different sources (indicated in the table).

Table 4-3 – Market discount rates per sector.

Sector	Discount Rate (%p.y.)	Source
Oil and Gas E&P	12	Moore (2009)
Refining	12	Moore (2009)
Biofuels	10	Banco Mundial (2014)
Mineral Extraction	15	De Gouvello (2010)
Biomass Extraction	15	De Gouvello (2010)
Electric Generation	10	EPE (2014)
Transport	12	Based on BCB (2015)[44]
Agriculture	15	Personal contact
Buildings	23	Miranda (2013)
Food and Bev.	15	De Gouvello (2010)
Ceramics	15	De Gouvello (2010)
Cement	15	De Gouvello (2010)
Mining	12	De Gouvello (2010)
Iron	15	De Gouvello (2010)
Iron Alloys	15	De Gouvello (2010)
Non-ferrous	15	De Gouvello (2010)
Other industries	12	Personal contact
Pulp and Paper	15	De Gouvello (2010)
Chemical	17	Personal contact
Textile	18	Personal contact

Source: Own Elaboration.

It is important to highlight that adopting different market discount rates per sector is supposed to be the situation that reflects more closely the reality, in which different sector have different levels of scale and access to capital. The exercise of adopting a unique market discount rate for the whole sector, assuming the premise that some policy instruments may eliminate asymmetries between sectors was also made by generating a scenario in which all processes are discounted at a 15% discount rate. Moreover, as the adoption of a unique discount rate when evaluating energy systems is commonly adopted, the comparison of these two scenarios might give some insight on the implications of this premise to the technology mix and emissions level. This rate was chosen based on the fact that most of sectors discount their investments at that level.

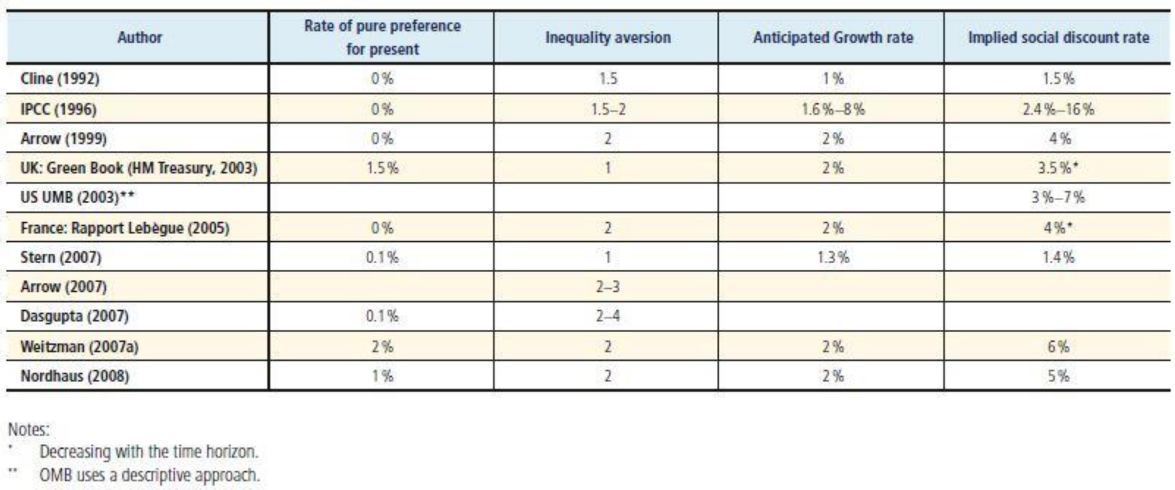
4.4.2.2 Social Discount Rate

As discussed in chapter 3, there are two approaches to discounting: the ethical (prescriptive) approach under which specialists recommend which rates should be applied; and the descriptive approach, under which adopted discount rate should reflect rates adopted by people (savers and investors) on their everyday decisions. Markandya et al. (2001) point out that ethical discount rates are relatively low, whereas descriptive discount rates tend to be higher.

Kolstad et al. (2014) say that aggregating costs and benefits of alternative actions is difficult in the light of climate change decisions. This happens because benefits of mitigation will materialize only in the distant future, but costs are born today. The Ramsey rule, however, may provide a good approximation of the social discount rate to be applied to consumption. Furthermore, the authors highlight that it is a judgement by the policymaker on the choice of adequate parameters of the Ramsey rule, and consequently the social discount rate.

In Table 4-4 below, it can be seen different calibrations for discount rate based on the Ramsey rule, most of them reflecting developed country experience. It may be observed that social discount rates may range from 1.4% to 16% p.y., where most of them are under the limit of 5% p.y.

Table 4-4 – Calibration of the discount rate based on the Ramsey rule.



Author	Rate of pure preference for present	Inequality aversion	Anticipated Growth rate	Implied social discount rate
Cline (1992)	0%	1.5	1%	1.5%
IPCC (1996)	0%	1.5–2	1.6%–8%	2.4%–16%
Arrow (1999)	0%	2	2%	4%
UK: Green Book (HM Treasury, 2003)	1.5%	1	2%	3.5%*
US UMB (2003)**				3%–7%
France: Rapport Lebègue (2005)	0%	2	2%	4%*
Stern (2007)	0.1%	1	1.3%	1.4%
Arrow (2007)		2–3		
Dasgupta (2007)	0.1%	2–4		
Weitzman (2007a)	2%	2	2%	6%
Nordhaus (2008)	1%	2	2%	5%

Notes:
* Decreasing with the time horizon.
** OMB uses a descriptive approach.

Source: Kolstad et al. (2014).

Markandya et al. (2001) cites 3% p.y. as a lower rate based on the ethical considerations, which is within lower range of discount rates shown in Table 4-4. Therefore, this is the social discount rate adopted for the purpose of this thesis, considered to be coherent with a prescriptive approach that takes into consideration the intergenerational issue as it values more future periods than higher descriptivist discount rates.

4.4.2.3 Declining Discount Rate

Kolstad et al (2014) state that 'despite disagreement on the empirical approach to estimating the discount rate, the literature suggests consensus for using declining discount rate over time' when attempting to evaluate climate change issues. Indeed, the adoption of declining discount rates deals with the intergenerational issue, rising the value of future welfare compared to present welfare and also deals with uncertainty of consumption and welfare of future generations, as explained in chapter 3.

For the purpose of this thesis, a storyline was created in order to justify the decline of discount rates from market levels to social levels within the time horizon considered by the model (2010-2050)[64]. Under this approach, it is acknowledged that economic sectors have,

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[64] This is considered a steep decline if compared to similar approaches found in literature. HM Treasury from United Kingdom, for example, adopt a 3.5% discount rate declining to 1% for costs and benefits received more than 300 years in the future (Harrison 2010).

today, a descriptive approach towards discount rate choice, i.e., they tend to adopt rates that reflect each opportunity cost of capital. However, it is assumed also that society acknowledges the value of future generations in the light of climate change debate and, hence, it makes an effort to reduce perception of risk and access to capital, making discount rates converge to social levels. Moreover, as Brazil might develop with high growth rates as a developing country, it is expected that in the long distance future it reaches developed country levels of consumption and time preference, which reflects in lower discount rates. This perspective also addresses the issue of uncertainty about costs and benefits accrued in the future[65], since it considers the reduction of discount rates along the time horizon.

In order to estimate the declining pathway of discount rates, Ramsey equation was adjusted in order to add the time factor, making discount rate change over time and decline exponentially:

$$r = ro + ni*e^{-gt}$$

(Equation 4-4)

Once parameters *ro*, *ni* and g were specified, the declining pattern of the curve defining r was applied to the market discount rates presented in the previous section, resulting in the declining discount rates listed in Table 4-5. For the purpose of this thesis, parameter *ro* (rate of pure preference for the present) was set in 1%[66], *ni* (elasticity of consumption – inequality aversion factor) was set in 2[67], and the growth rate was set in 4%[68].

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[65] Although (Equation *3-3* was not adopted in this case.

[66] As in Nordhaus (2008) and HM Treasury (2003).

[67] As in Arrow (1999), HM Treasury (2003), Rapport Labègue (2005), Weitzman (2007) and Nordhaus (2008).

[68] This is based on the average growth established by EPE (2014).

Table 4-5 – Declining discount rates per sector (%p.y.)

Sector	Discount Rates								
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Oil and Gas E&P	15	12	10	8	7	6	5	4	3
Refining	12	10	8	7	5	4	4	3	2
Biofuels	10	8	7	6	5	4	3	3	2
Mineral Extraction	15	12	10	8	7	6	5	4	3
Biomass Extraction	15	12	10	8	7	6	5	4	3
Electric Generation	10	8	7	6	5	4	3	3	2
Transport	12	12	10	8	7	6	5	4	3
Agriculture	15	12	10	8	7	6	5	4	3
Edifications	23	19	15	13	10	9	7	6	5
Food and Bev.	15	12	10	8	7	6	5	4	3
Ceramics	15	12	10	8	7	6	5	4	3
Cement	15	12	10	8	7	6	5	4	3
Mining	12	10	8	7	5	4	4	3	2
Iron	15	12	10	8	7	6	5	4	3
Iron Alloys	15	12	10	8	7	6	5	4	3
Non-ferrous	15	12	10	8	7	6	5	4	3
Other industries	12	10	8	7	5	4	4	3	2
Pulp and Paper	15	12	10	8	7	6	5	4	3
Chemical	17	14	11	9	8	6	5	4	4
Textile	18	15	12	10	8	7	6	5	4

Source: Own Elaboration.

4.4.3 Climate Policy Restrictions

This sections details the premises of carbon policies tested in TIMBRA. It was adopted the cap restriction approach that should correspond to Brazil’s INDC. Different premises regarding foresight (anticipation) and time decision to engage in climate policies were also tested in order to evaluate how timing issues may impact investment decision and the long-term technology mix of the energy sector.

4.4.3.1 Cap scenarios

Cap scenarios adopted in TIMBRA were based on caps estimated by Spencer et al. (2015) and reflected the absolute target of Brazilian INDC for 2030: 1.2 $GtCO_2eq$. This is a global target that accounts for not only emissions in the energy sector, but also emissions for agriculture, forestry and other land use (AFOLU). Emissions for the energy sector were estimated by the authors by estimating scenarios consistent with INDC targets for the AFOLU. Based on this, an emission budget for the energy system was created, leading to a cap of 575.8 million tons of CO_2 per year starting from 2030. The choice of working with annual cap is also in accordance with the study of Spencer et al. (2015).

As it will be better detailed in next sections, TIMBRA also considered scenarios in which delayed action related to climate change mitigation were adopted, which means that the effort to mitigate starts later than 2030, more precisely, in 2040. To estimate emission caps for delayed scenarios, the cumulative abated emissions in the early action scenarios (with the 575.8 $MtCO_2$ annual budget[69]) was obtained. Then, this cumulative emission was distributed equally along the 2040-2050 period and from that distribution it was obtained a new annual emission cap for the system. This new cap is supposed to be more stringent, i.e., lower, than caps for early action scenarios, since there is less time left to cope with cumulative emissions target that is equal for both early and delayed action scenarios. Table 4-6 summarizes cap restrictions obtained for each case:

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[69] It should be noted that, since the three baseline scenarios have different discount rates, it is expected that CO2 emissions in each case are also different.

Table 4-6 – Annual emission caps per scenario.

Scenario	Emission Cap ($MtCO_2eq$)
Early Action Scenarios (from 2030)	575.8
Delayed Action – Social (from 2040)	508.0
Delayed Action – Market (from 2040)	500.6
Delayed Action – Declining (from 2040)	496.2

Source: Own Elaboration.

4.4.3.2 Foresight and Timing of climate effort

Studies exploring non-idealized international implementation of climate policies have been conducted since 2009, as showed in Clarke et al. (2014). As idealized implementation scenarios are the ones that hold the assumption that mitigation is undertaken where and when it is least expensive[70], the reality shows that countries and regions undertake mitigation efforts at different times and with different approaches.

Even though TIMBRA constitutes a country-level model, not a global level model, it is still possible to mimic non-idealized behavior by two ways. The first one consists of those scenarios in which near-term behavior in terms of mitigation is inconsistent, i.e., typically less than what would be needed to cope with long-term goals at minimum cost. In this thesis we call this type of scenario “myopic” because it does not foresee the benefit of taking early action regarding climate change. This ‘constrained near-term ambition’ favors conventional technologies and lead to technological lock-ins, as demonstrated in Riahi et al. (2015) and Schaeffer et al. (2013). Therefore, they might increase cost of policy or even make policy unfeasible, since it demands a great effort in later periods to cope with low carbon policies, depending on its stringency.

Therefore, in order to foster non-ideal behavior and verify the effects of technological lock-ins on climate policies, myopic scenarios are opposed to perfect foresight scenarios in

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[70] They are also denominated ‘cost-effective’ scenarios, since they ‘lead to the lowest aggregate global mitigation costs under idealized assumptions about the functioning of markets and economies (Clarke et al. 2014).

this thesis. Perfect foresight scenarios are not constrained in the first periods and they optimize over time so that all future decisions are taken into account in the present, i.e., there is an anticipation of the climate policy and mitigation efforts may start before the policy is put into effect. On the other hand, myopic vision scenarios have their first periods (before climate policy is on) fixed to the base case scenarios (for each discount rate) and, thus, they do not anticipate climate policies and are attached to conventional technologies.

The second approach consists just in delaying action regarding climate change mitigation, i.e., assuming that policies that should have started in one period will start one or two periods later. This type of scenario makes more sense with cap restrictions, in which, under the delayed scenario, a fixed amount of cumulative abatement should be reached in less time. Therefore, for the thesis we assume delayed action scenarios with cap restriction to oppose early action scenarios, the latter reflecting idealized behavior. We did not test delayed action scenarios in carbon price scenarios because, since it would constitute a delay in pricing, not in cap, it would result only in a delay in technology penetration curve of low carbon technologies, which do not necessarily reflect the need of more stringent action to cope with the policy.

As early action cap scenario policies start in 2030, it was defined that delayed action cap scenario policies start in 2040. In order to obtain cap constraints of delayed action scenarios, it was assumed that all cap scenarios (both early and delayed action) should reach the same cumulative cap, resulting in more stringent annual caps for the delayed action scenarios. The caps for delayed action scenarios were listed in Table 4-6.

It should be mentioned that early, delayed, perfect foresight and myopic scenarios also brings to light the time preference for investing in low carbon options either due to lock-in issues or to barriers to adoption that delay engagement in low carbon technologies. Each perspective overlapped to other timing issues lead to a different investment profile choice at distinct periods. This should give insight about technology mix resultant from different policy decisions and about costs of different levels of engagement to mitigate.

4.4.4 Scenarios Consolidation

Based on the descriptions given above, a set of sixteen scenarios was generated in order to evaluate how different approaches to time preference should impact Brazil's energy sector. The tree set of scenarios in Figure 4-4 show how scenarios are grouped from the baseline, with market discount rates to low carbon policy scenarios with different discount rates:

- "BASE" refers to baseline, either primary or secondary, scenarios in which no low carbon policy is applied;
- "LC" refers to low carbon scenarios, the alternative scenarios;
- "MKT" refers to a unique market discount rate and "MKTS" refers to different market discount rates per sector;
- "SOC" refers to a unique social discount rate;
- "DDRS" refers to declining discount rates per sector;
- Ending with "M" refers to scenarios with myopic vision, which implies the existence of lock-in effects;
- Ending with "PF" refers to scenarios with perfect foresight, which implies in no barriers to the entrance of new technologies;
- Ending with "MD" refers to scenarios with myopic vision and delayed action related to mitigation; which implies in lock-in effects added to the effects of fragmented global commitments towards climate change;
- Ending with "PFD" refers to scenarios with perfect foresight and delayed action related to mitigation; which implies in no barriers to new technologies, but global fragmented commitments towards climate change;

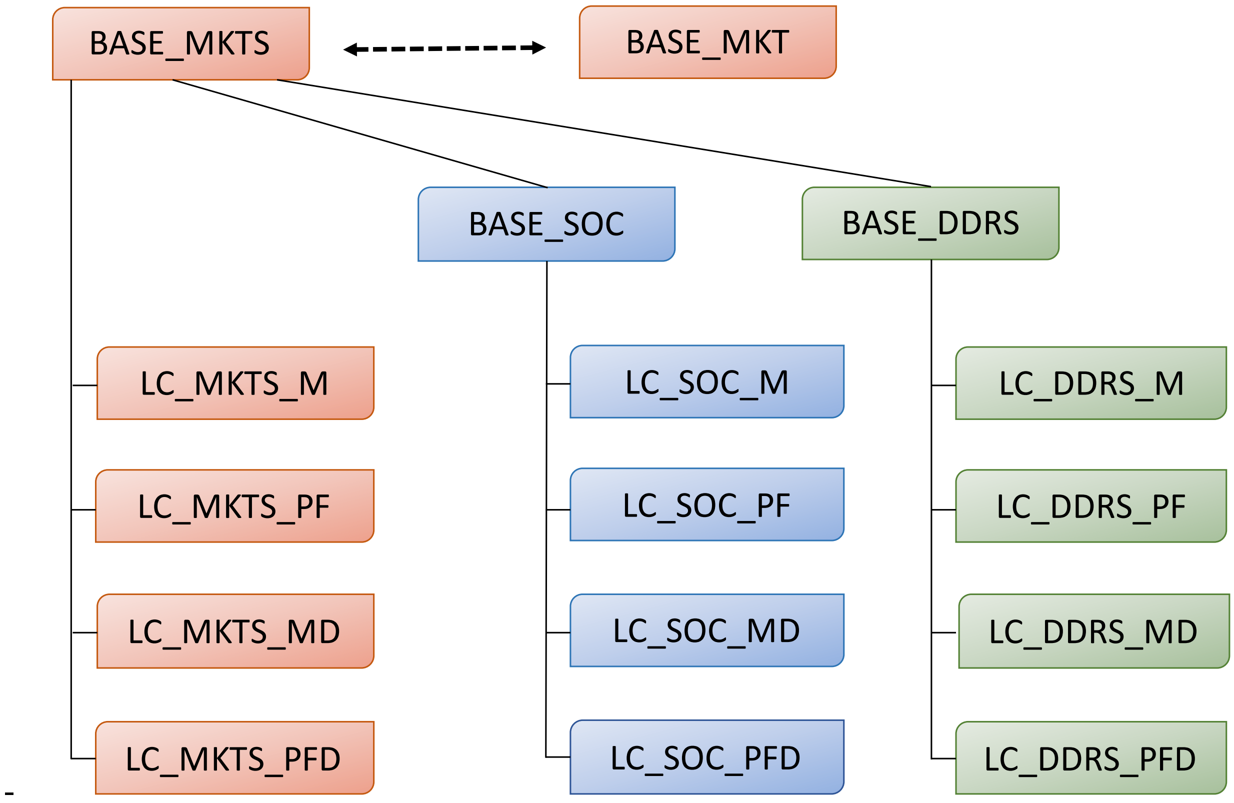

Figure 4-4 – Defined Scenarios

Based on this figure, it is possible to infer that the baseline (counterfactual) scenario is scenario BASE_MKTS, which considers descriptive discount rates, differentiating them across the different economic sectors. The scenario with constant market discount rate (BASE_MKT) is not considered as a source of alternative scenarios, being only compared with BASE_MKTS in order to identify how a homogeneous and a heterogeneous set of discount rates per sector can affect the least-cost solution in TIMBRA.

Moreover, the base case scenarios BASE_MKTS, BASE_SOC and BASE_DDRS with different discount rate premises are equivalent scenarios as they do not include low carbon policies, even though BASE_MKTS is the baseline that should be the main case to compare results to. Results of these three scenarios should be compared in order to identify the consequences of different approaches regarding time preference, reflected in the discount rate choice. In addition, from each of these three base cases will derive the alternative scenarios with low carbon policies subject to the effect of technological lock-in (expressed by myopic vision) and fragmented global commitments (expressed in delayed action in terms of climate policy).

5 Results and Discussion

With a set of sixteen scenarios, it is important to organize results in order to infer the outcomes properly. In that sense, results were divided into separate items in order to depict and to discuss the specific effect of each dimension considered in the analysis. First, the results of the main baseline scenario will be exposed, with market discount rates per sector (BASE_MKTS), also exposing the differences between this scenario and the scenario with a unique market discount rate (BASE_MKT). Then, the differences of the three reference scenarios (BASE_MKTS, BASE_SOC and BASE_DDRS) will be discussed in order to identify the effect of discount rate choice without climate policy action. Afterwards, the differences in results for scenarios with perfect and myopic foresight and with early and delayed action related to climate mitigation will be discussed. After these analyses, it is possible to discuss how each set of scenarios evolves in terms of technology portfolio and discuss the differences in their total costs, which is an indicator of cost of policies.

5.1 Baseline: market discount rate per sector

The results derived from scenario BASE_MKTS, considering specific market discount rates per sector show a significant reliance on fossil fuels, as Figure 5-1 (domestic primary energy supply) shows. Coal, natural gas and oil resources account for 65% of domestic primary energy supply in 2050, while biomass and biofuels account for 20%. Hydro has only a 12% share, reflecting the exhaustion of potential outside Amazon basin and nuclear and “other renewables”, such as wind and solar, are only 1% of primary energy supply.

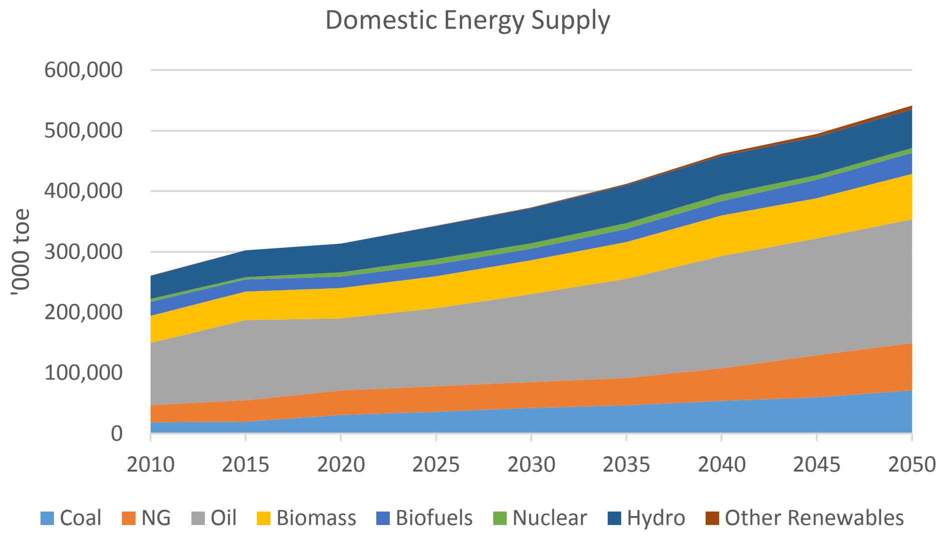

Figure 5-1 – Domestic primary energy supply of scenario BRA_MKTS.

Electric generation figure (Figure 5-2) shows that in the long term the hydro power will still play an important role in electric matrix, although its relative share reduces over time (from 76% in 2010 to 54% in 2050). Also, it shows that coal and natural gas are also important energy sources for the sector, reflecting 16%[71] and 19%, respectively, of electric generation in 2050. Onshore wind energy plays a small part in figures, as it is no more than 5% of generation.

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[71] Including co-firing with biomass.

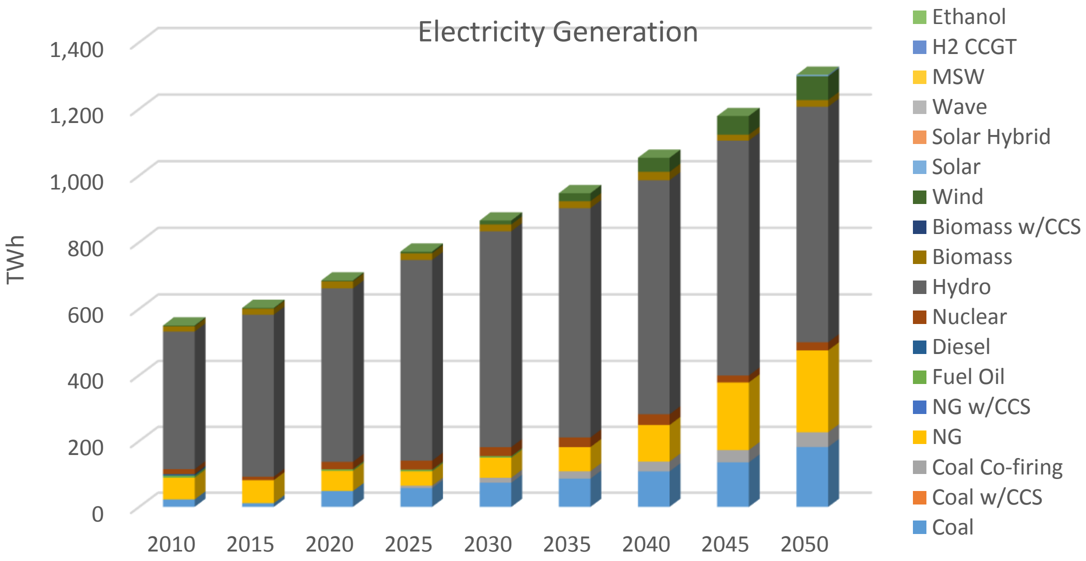

Figure 5-2 – Electricity generation per source of scenario BASE_MKTS.

Transport sector, as may be observed in Figure 5-3, show heavy reliance on fossil fuels either in passenger transport, dominated by internal combustion engine (ICE) flex fuel vehicles[72] in the private transport and ICE diesel buses in public transport, or in freight transport through ICE diesel trucks.

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[72] Flex vehicles use blended gasoline and ethanol. Blended gasoline is heavily used until 2040, when it starts to give space to ethanol.

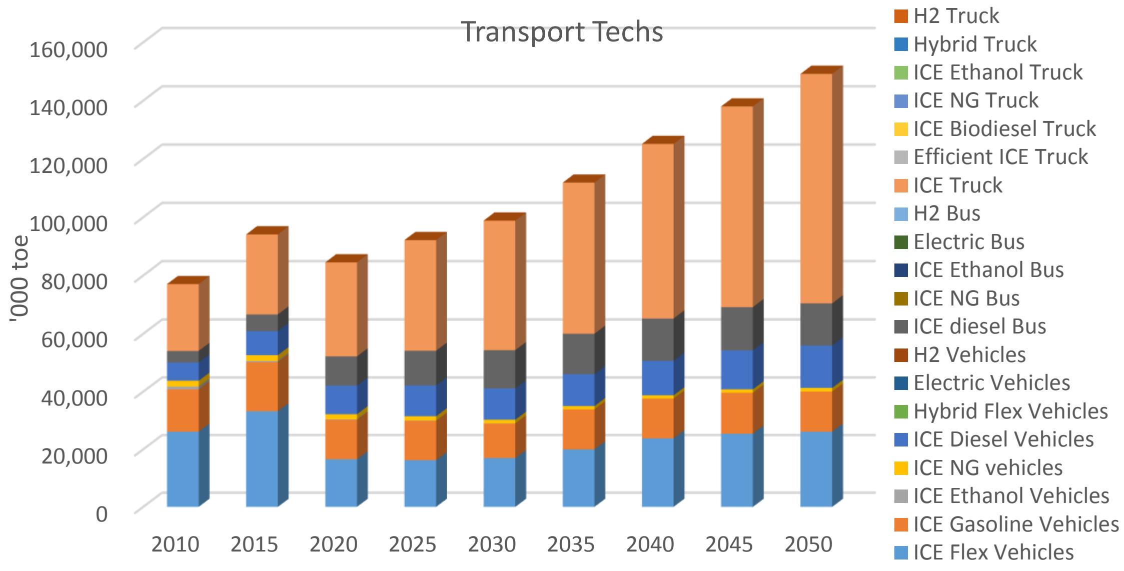

Figure 5-3 – Transport sector technologies in scenario BASE_MKTS.

Industry shows heavy reliance in oil products and other fossil fuel resources, such as coal and natural gas, as observed in Figure 5-4. Bagasse is a renewable source with significant share due to demand in the food and beverages industry. It is worth noticing that the results for industry did not vary much across scenarios, as it can be observed when analyzing all results in Annex A.

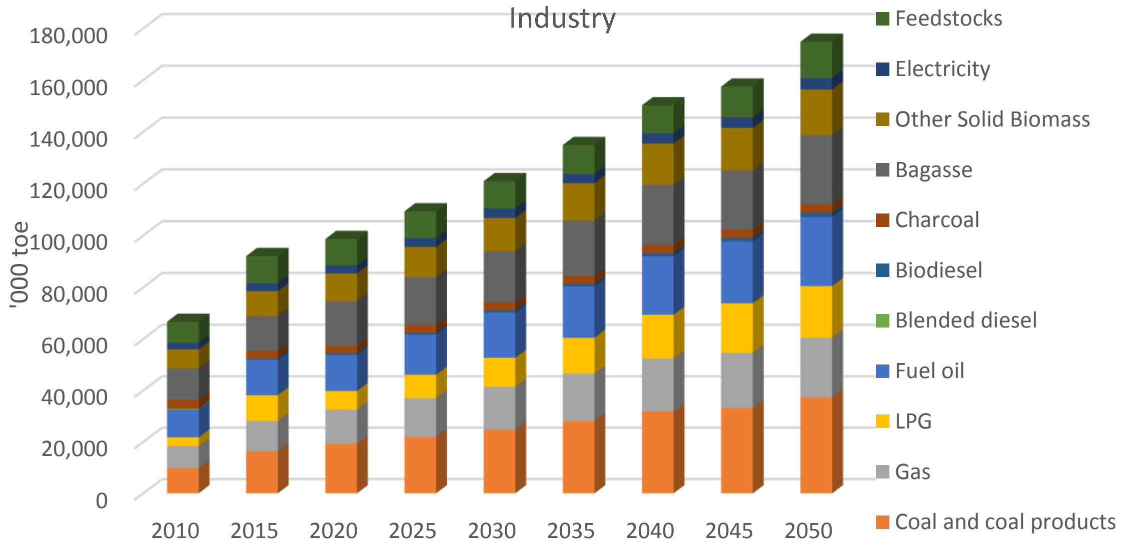

Figure 5-4 - Industrial energy consumption per source in scenario BASE_MKTS.

Finally, CO_2 emissions present a significant increase from 2010 to 2050, as it can be seen in Figure 5-5. Emissions rise from 440 $MtCO_2$ in 2010 to 1.182 $MtCO_2$ in 2050 reflecting the great increase in demand due to economic growth premises and the reliance in fossil fuels in order to supply that demand.

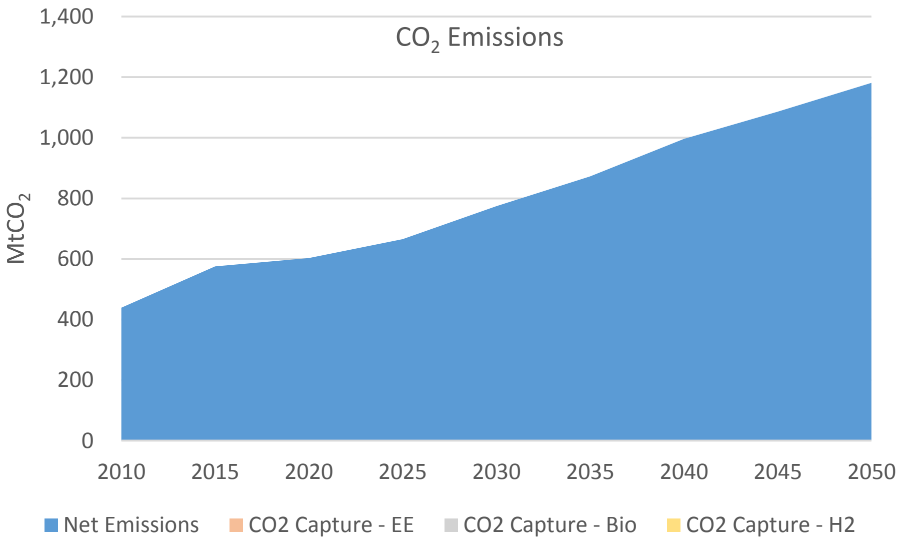

Figure 5-5 – CO_2 emissions in scenario BASE_MKTS.
(Note: net emissions correspond to gross emissions minus captured emissions by CCS technologies, when these technologies are adopted.)

As discussed when scenarios were defined (section 4.4), scenario BASE_MKTS should reflect a situation close to real world, where different sectors have different levels of access to capital and agents tend to evaluate their potential projects considering their perception of opportunity cost of capital and risk. It is common, also, when evaluating energy systems, to discount cash flows with a unique discount rate. The comparison of scenario BASE_MKTS (different discount rates per sector) with scenario BASE_MKT (unique discount rate), indeed, shows that these different premises incur in different least cost technology mix options and discrepancies in CO_2 emissions level.

Figure 5-6, for example, shows that, in fact, scenario BASE_MKT presents a greater reliance on coal, displacing mainly natural gas supply when comparing to scenario BASE_MKTS. It can be also noted that renewable sources supply is also reduced in scenario BASE_MKT when compared to scenario BASE_MKTS, since biomass, biofuels and other renewables (mainly wind energy) is less adopted. This difference becomes clearer when electricity generation figures are exposed (Figure 5-7), since it shows a higher coal use in scenario BASE_MKT and a very small use of natural gas and wind source in this scenario when compared to scenario BASE_MKTS.

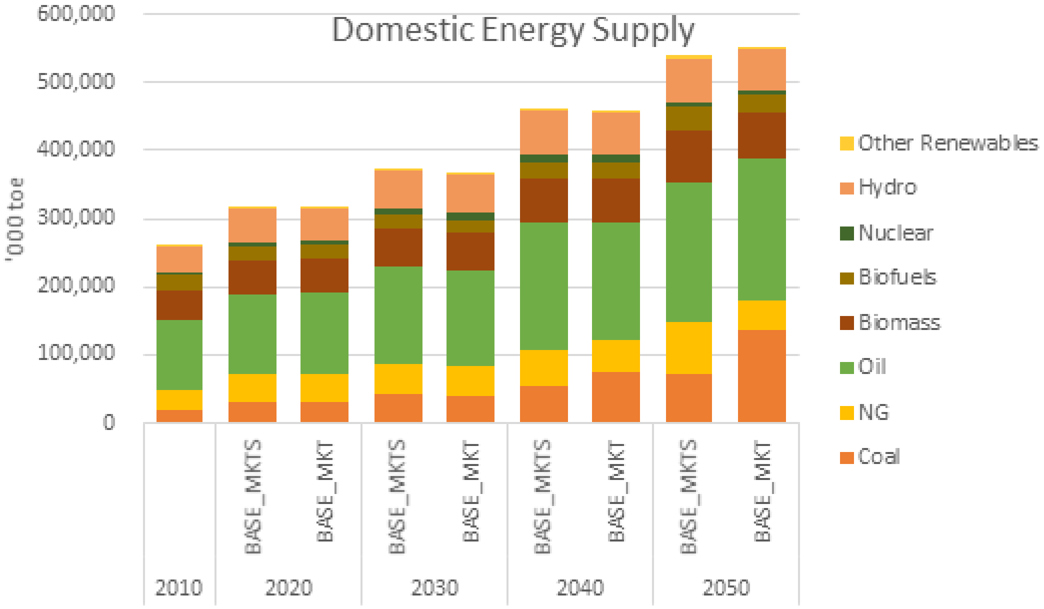

Figure 5-6 – Comparison of domestic primary energy supply between scenarios BASE_MKTS and BASE_MKT.

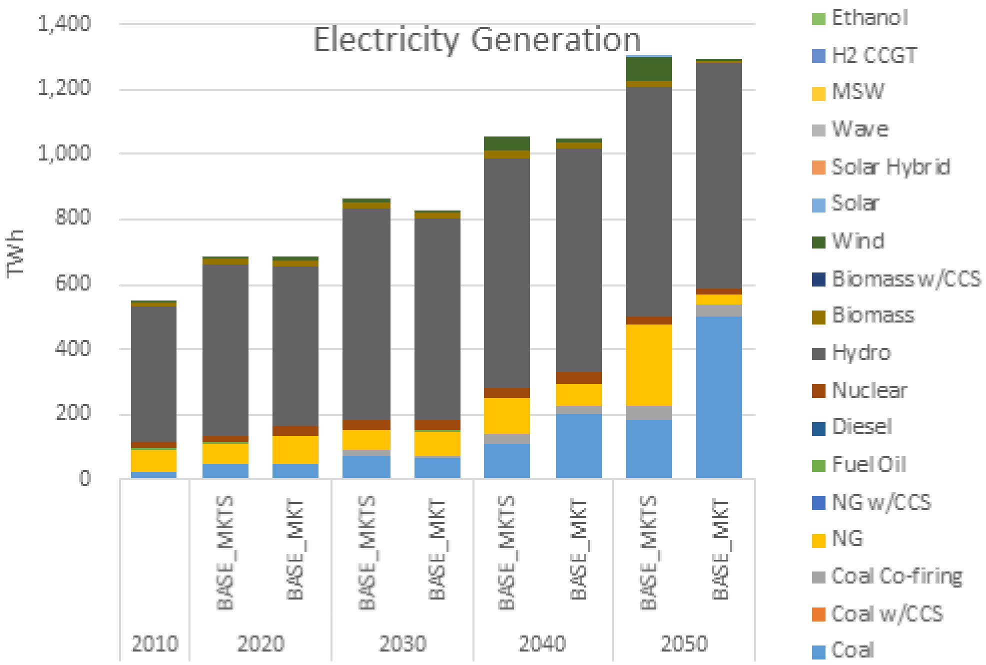

Figure 5-7 – Comparison of electricity generation per source between scenarios BASE_MKTS and BASE_MKT.

CO_2 emissions figure (Figure 5-8) shows that in the long-term a unique discount rate result in an even more carbon-intensive scenario, with emissions level reaching 1.418 $MtCO_2$ in 2050, 20% higher than the scenario BASE_MKTS, with different market discount rates per sector. This is a natural consequence of an energy system that is very reliant on coal source and because the discount rate adopted is above market levels for some sectors, such as oil refining and bioenergy.

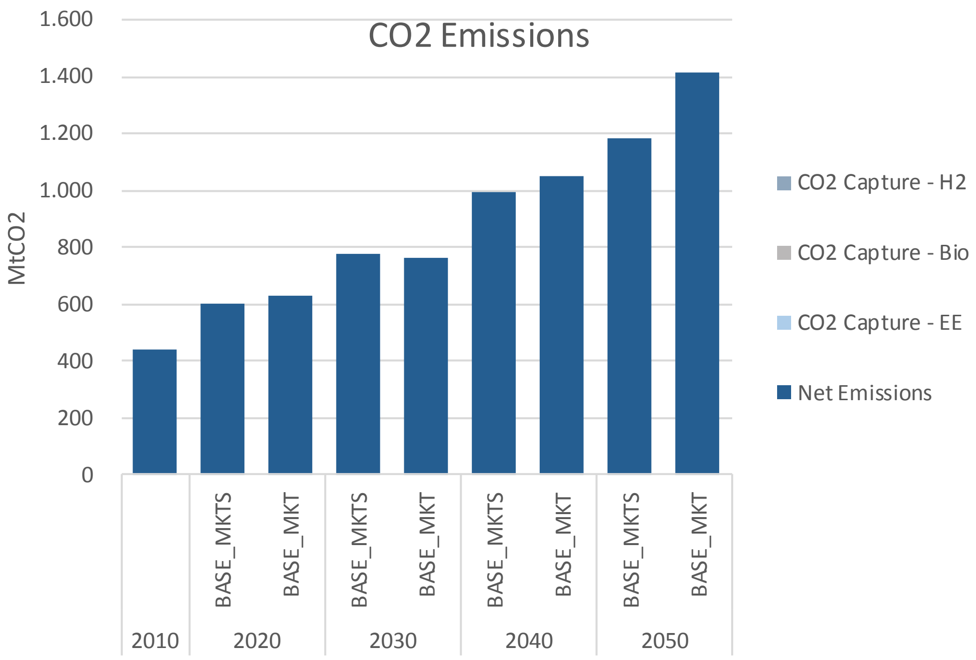

Figure 5-8 – Comparison of CO_2 emissions between scenarios BASE_MKTS and BASE_MKT.
(Note: net emissions correspond to gross emissions minus captured emissions by CCS technologies, when these technologies are adopted.)

5.2 Base Cases Comparison

The three base cases differentiate from each other only by discount rate choice, having no other constraint that would translate a low carbon policy. Thus, it is important to compare them in order to evaluate how discount rate choice might affect technology portfolio in each case and, hence, CO_2 emissions.

Figure 5-9 shows Brazil´s domestic primary energy supply[73] per source in 2010, 2020, 2030, 2040 and 2050 for each of base case scenarios: scenario BASE_SOC – social constant discount rate; scenario BASE_MKTS – market constant discount rate per sector; and scenario BASE_DDRS – declining discount rate per sector. It is interesting to notice that scenario BASE_DDRS is the one with the lowest domestic energy supply between these three

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[73] Methodology adopted to account domestic energy supply in this chapter is the “direct equivalent method”. Under this method, there is an equivalence of 100% between primary energy and electricity or heat for all non-combustible renewable energy sources and nuclear energy (Stoffregen & Schuller 2014).

scenarios, which means that technology portfolio in DDR scenario is more efficient. Coal use seems to be approximately the same among scenarios, mainly used for power generation, while natural gas use is higher in BASE_MKTS because of high adoption of combined cycle natural gas power plants. Oil use is higher in this scenario and in BASE_SOC scenario because of high adoption for internal combustion engine (ICE) trucks in transport, as it will be observed in the next figures. Scenario BASE_DDRS is the one with higher biofuel usage, adopted broadly in transport sector, but the one with the highest biomass use is BASE_SOC, which is justified by the adoption of biomass power plants and by generation from sugarcane bagasse. This might also have influenced the results of this scenario, as biomass technologies, although "clean", are more inefficient. Hydropower is kept relatively the same among scenarios and nuclear presents a very small change. Scenario BASE_SOC is the one with the highest share of this source. It is worth noting also that "other renewables" are observed to have a higher share in BASE_SOC and BASE_DDRS scenarios, since these scenarios are the ones with higher adoption of wind and solar energy in electric sector.

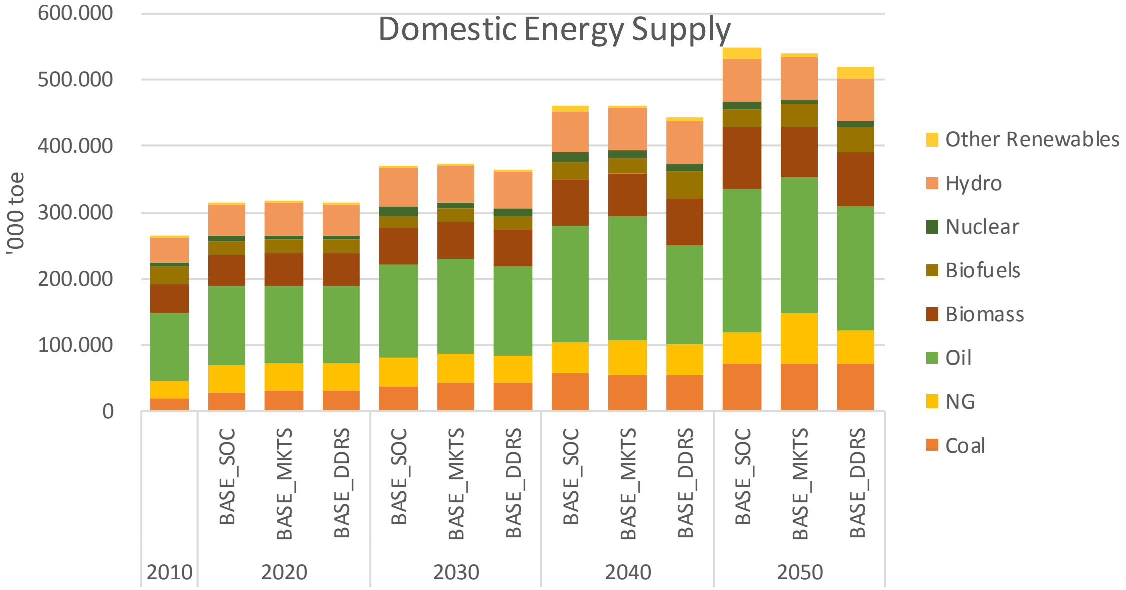

Figure 5-9 – Comparison of domestic primary energy supply between base case scenarios.

Final energy consumption per source also changed from one scenario to another and, again, scenario BASE_DDRS is the one with the lowest value. As some sources like coal, natural gas, fuel oil, jet fuel, LPG and electricity do not change significantly among scenarios, blended gasoline, blended diesel and ethanol have different levels of consumption depending on the scenario. This reflects the differences in the transport sector, since ethanol is adopted in BASE_MKTS scenario over other blended gasoline in flex fuels and in BASE_DDRS scenario over blended diesel in heavy vehicles. Industry and buildings sectors did not present significant changes among scenarios, which explains in some extent why many fuels remained constant in Figure *5-10*.

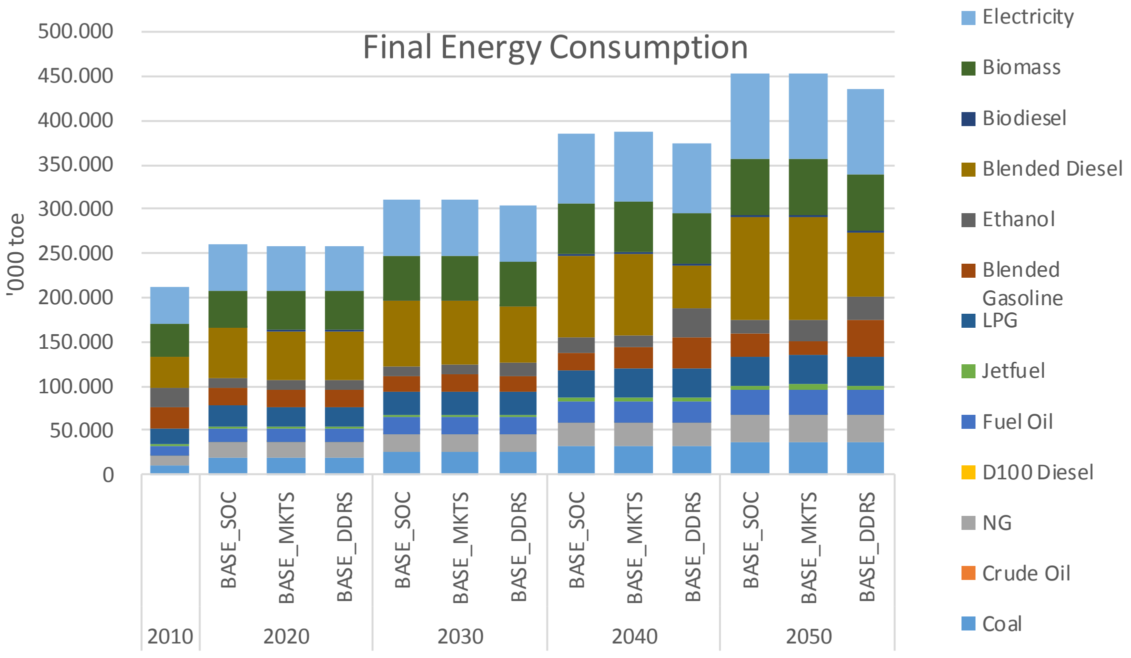

Figure 5-10 – Comparison of final energy consumption between base case scenarios.

When it comes to electricity generation, the most prominent differences depicted in Figure 5-11 is that BASE_MKTS uses significantly more natural gas power plants than the other two scenarios, installing a large number of combined cycle units. The other two scenarios tend to favor renewable sources: scenario BRA_BASE_C uses a considerable amount of wind energy (onshore and offshore) and also municipal solid wastes, while BRA_BASE_DDRS uses wind energy onshore and offshore combined with a significant share of solar energy from CSP and PV units. Hydropower, which presents the highest share, and coal remain practically unchanged among scenarios. Given that no policy is taken in these scenarios, these results show a strong signal that different discount rates may favor certain technologies over others.

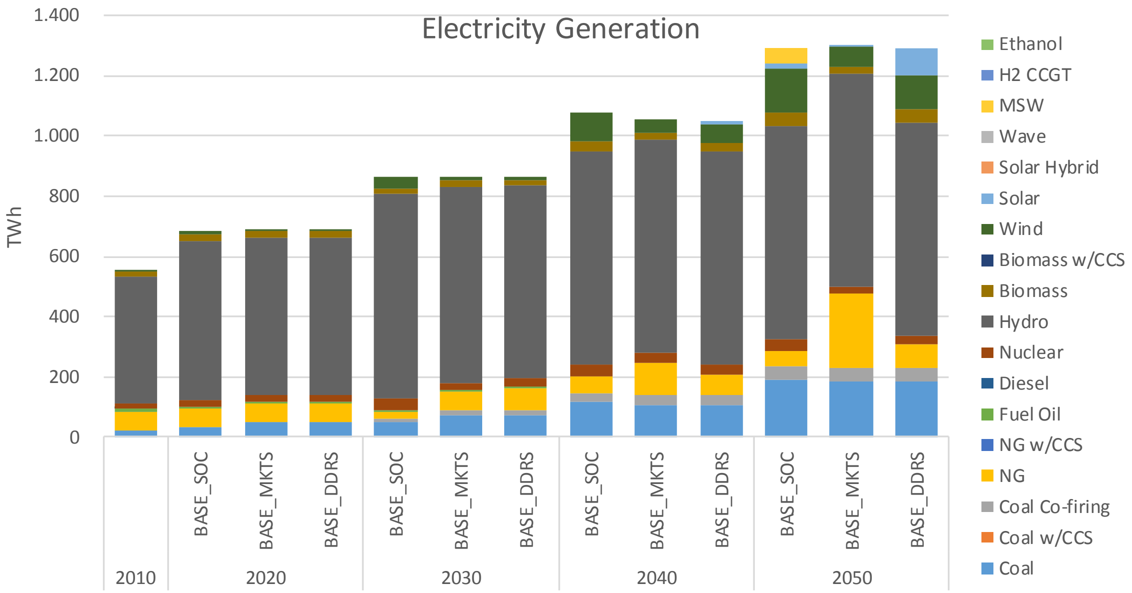

Figure 5-11 – Comparison of electricity generation per source between base case scenarios.

Regarding CO_2 emissions, Figure 5-12 shows emissions per period: except for 2020, when the three scenarios present the same level of emissions[74], in all periods the lowest emission scenario is BASE_DDRS, which is explained by the adoption of renewables like wind and solar in power sector and of ethanol in the transport sector. The highest emission scenario is the BASE_MKTS, which is driven mainly by the high usage of natural gas in the power sector. Indeed, cumulative emissions for BASE_SOC, BASE_MKTS and BASE_DDRS are approximately 6.9, 7.2 and 6.7 $GtCO_2$ respectively.

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[74] The fact that emissions were at the same levels in 2020 does not mean that the model was not free to choose a pathway in that period. It shows that in 2020 the least cost mix of technologies is pretty much the same.

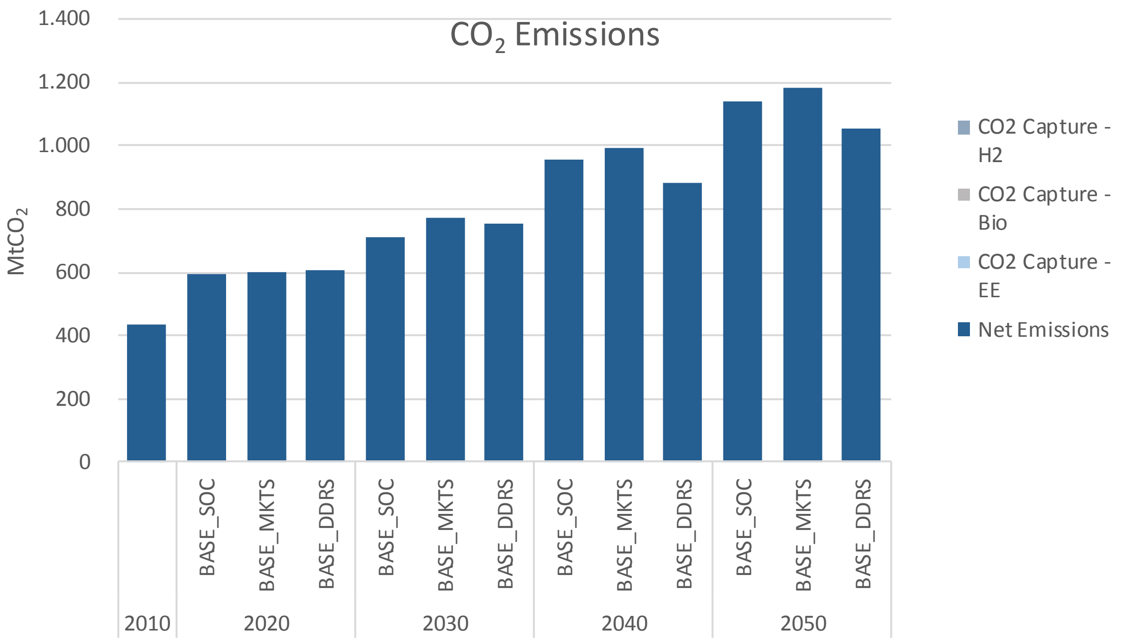

Figure 5-12 – Comparison of CO$_2$ emissions between base case scenarios.
(Note: net emissions correspond to gross emissions minus captured emissions by CCS technologies, when these technologies are adopted.)

Now the difference between base case scenarios with distinct discount rates were identified, it is possible to evaluate the effect of other elements that relates to time preference on low carbon policies and how the combination of policy and discounting effect can change technology portfolio of scenarios.

5.3 Climate policies and Technological Lock-in

The difference between scenarios with perfect and myopic foresight relies on the fact that myopic foresight does not anticipate any climate action before policy begins, since policy is disregarded by agents. This premise aggravates the technological lock-in incurred in the maintenance of investments in carbon-based technologies. Hence, it is expected difference between perfect foresight and myopic vision scenarios especially in the periods where policy begins, when agents in myopic scenarios have to run and compensate for the inactivity of before.

It was decided to expose in these sections the figures that indicates more prominently the differences across scenarios. More information regarding, for instance, domestic energy supply, is available in Annex A. For all three scenarios, it can be observed in electricity generation figures (Figure 5-13, Figure 5-14 and Figure 5-15) that in myopic scenarios coal generation without CCS did not completely phase-out, as happens in perfect foresight scenarios. It can also be observed mainly in market discount rates (MKTS_*) scenarios and in declining discount rate (DDRS_*) scenarios that myopic foresight allows a lower share of renewables than in perfect foresight scenarios. Both phenomena show that myopic scenarios are harder in fulfilling a significant transition in technology portfolio which is explained by the technological lock-in element that these scenarios include.

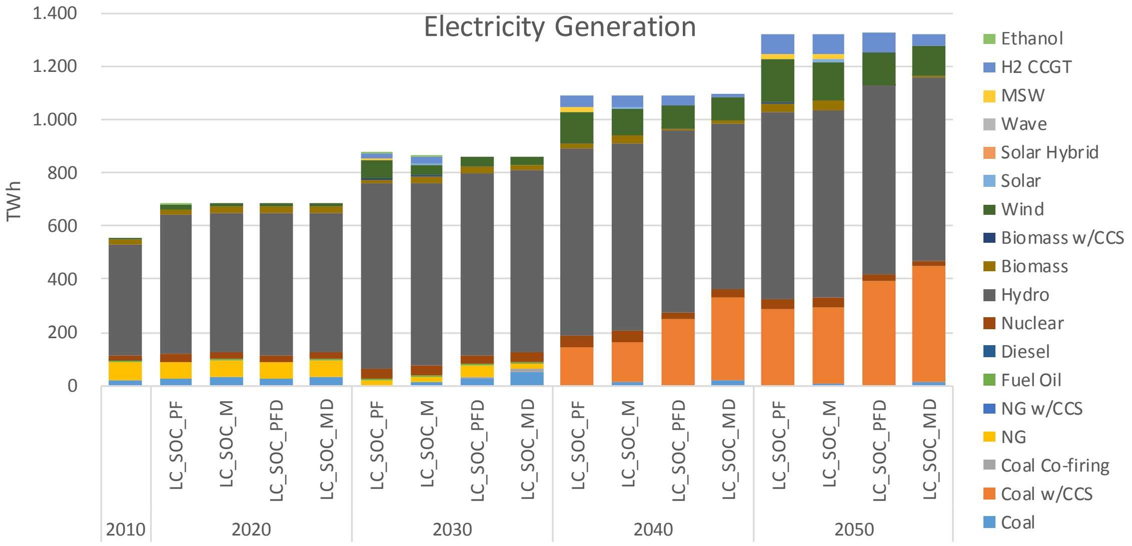

Figure 5-13 – Comparison of electricity generation between cap restricted scenarios under perfect foresight and myopic vision, social discount rates.

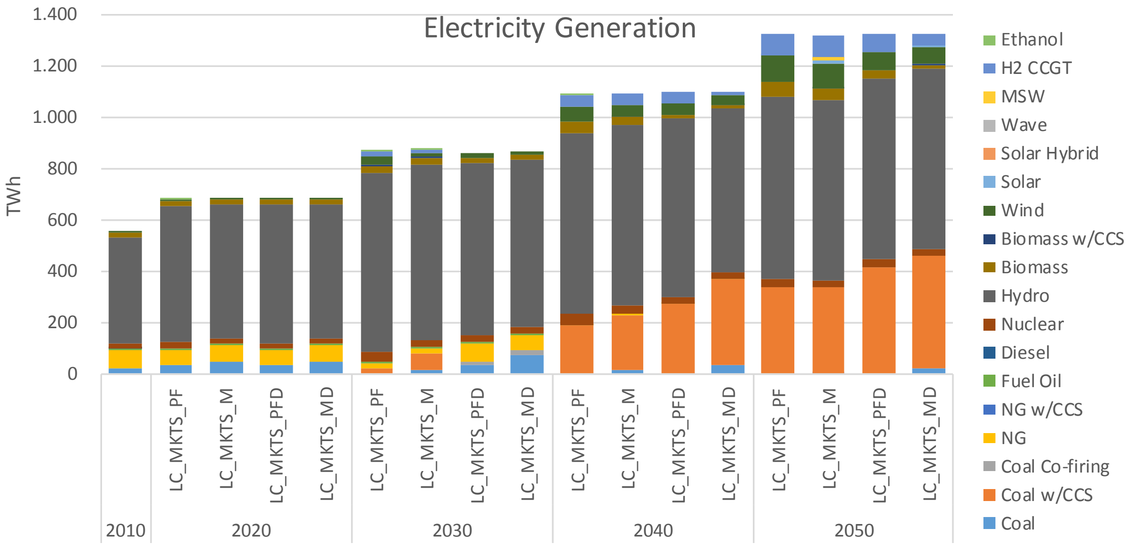

Figure 5-14 – Comparison of electricity generation between cap restricted scenarios under perfect foresight and myopic vision, market discount rates.

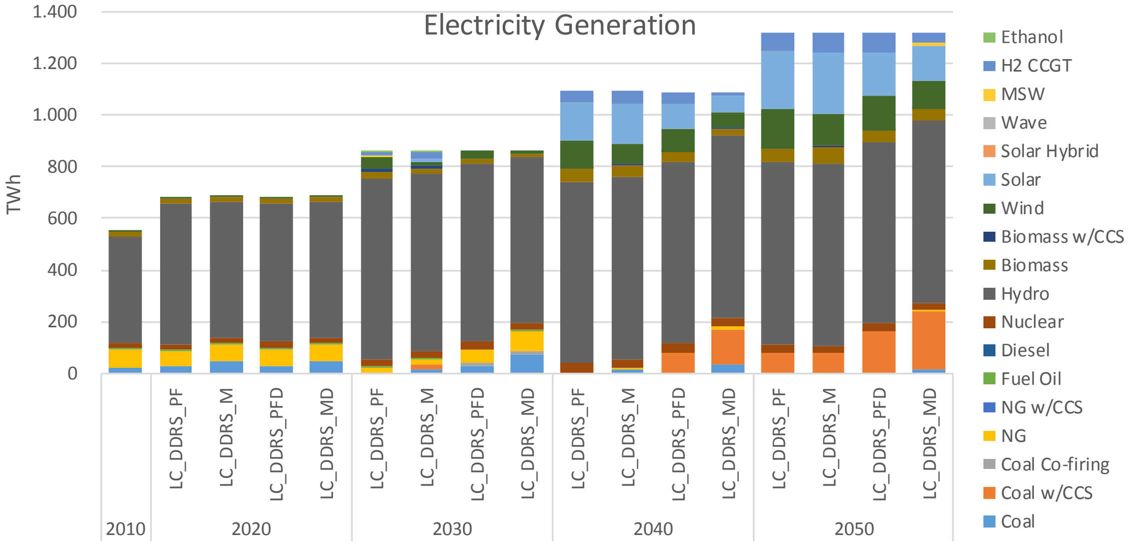

Figure 5-15 – Comparison of electricity generation between cap restricted scenarios under perfect foresight and myopic vision, declining discount rates.

It may be interesting also to observe changes in the transport sector (Figure 5-16, Figure 5-17 and Figure 5-18), since some differences can also be seen in social discount rate scenarios (SOC_*) and in declining discount rate scenarios (DDRS_*). Myopic scenarios show that internal combustion engine (ICE) technologies with fossil fuels are harder to phase-out to give space to new technologies. In delayed action scenarios with social discount rates, diesel buses do not completely phase-out until the end of time horizon in order to give space to ethanol buses. In fact, in the delayed myopic scenario almost no ethanol buses are adopted. Similarly, it can be observed in declining discount rates scenarios how, in 2030, ethanol trucks are adopted in a less extent in myopic scenarios when compared to their perfect foresight version. Once again, the fact that before policy starts the model is attached to a "business-as-usual" behavior delays the transition to a low carbon energy system.

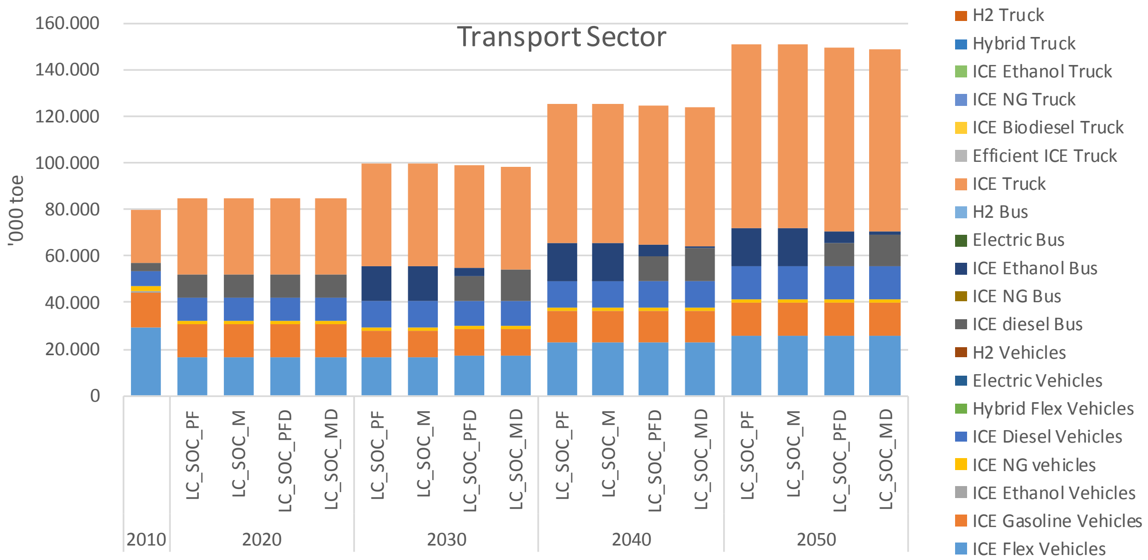

Figure 5-16 – Comparison of transport technologies between cap restricted scenarios under perfect foresight and myopic vision, social discount rates.

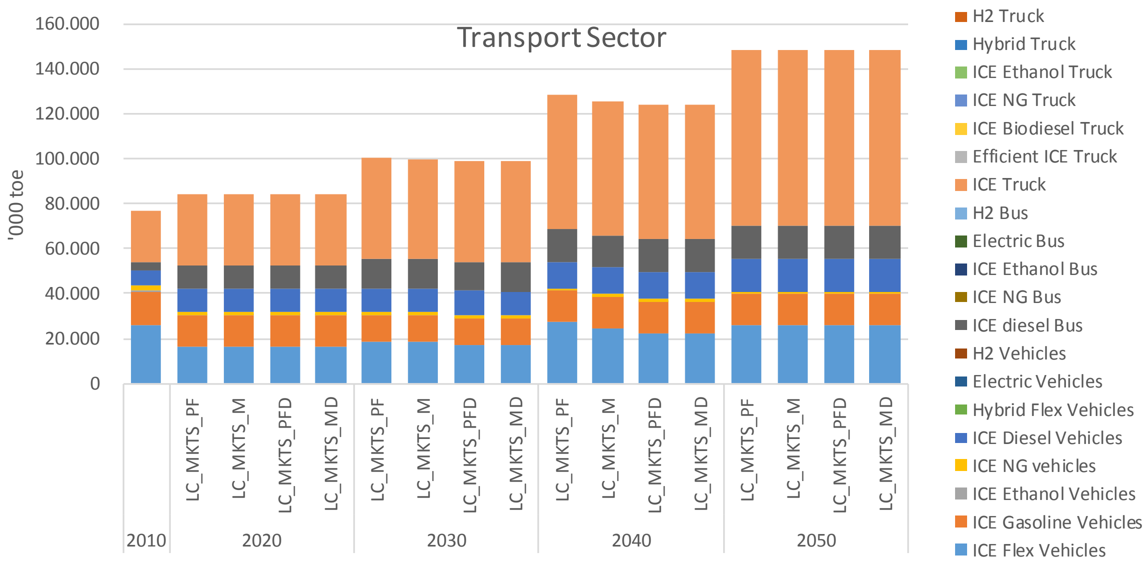

Figure 5-17 – Comparison of transport technologies between cap restricted scenarios under perfect foresight and myopic vision, market discount rates.

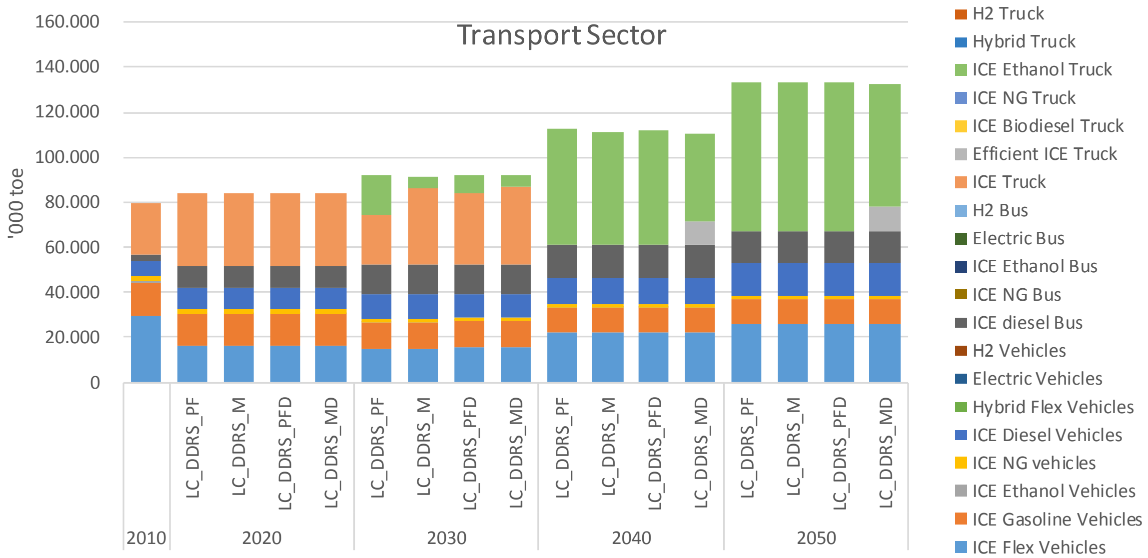

Figure 5-18 – Comparison of transport technologies between cap restricted scenarios under perfect foresight and myopic vision, declining discount rates.

5.4 Climate Policy and Timing of Action

Delayed action scenarios were included in the analysis in order to make it possible to evaluate how decision of when to engage in low carbon policy may affect the energy system and how impacts change depending on the discount rate adopted. This also brings to light the point about time preference and how it affects the low carbon transition in an energy system. Although something has been discussed when perfect foresight and myopic vision scenarios were compared (item 5.3), in this item discussion will be focused on the differences of early action and delayed action scenarios as an attempt to identify and "isolate" effects.

Main differences across scenarios are easier to observe in electricity generation, transport sector and carbon emission figures, although something can be inferred looking at domestic energy supply figures[75]. In terms of social discount rates, Figure 5-19, as expected, shows that fossil fuels have a higher share of domestic energy supply in delayed action scenarios than in early action in all periods, giving less space to renewables. This is corroborated by Figure 5-20, where it is possible to check the evolution of electricity generation: as early action scenarios are quicker in phasing-out non-CCS coal and natural gas power plans, on the other hand they install a smaller amount of retrofits and new coal power plants with CCS than delayed action scenarios. This behavior is expected and it happens because, when late action occurs, less time is available to mitigate and, hence, the model has to adopt quick and high-abatement technologies to cope with low carbon policies. It is also possible to observe in delayed action scenarios that coal plants with CCS take space from renewables, since wind, solar and MSW are less used in these scenarios. This happens because CCS is an option that mitigates a bigger amount of CO_2 per period and, therefore, is the option that enables the scenario to cope with the carbon policy within the policy period. Hydrogen combined cycle gas turbines (H_2 CCGT) are adopted in the four scenarios considered, showing that this technology plays an important role regardless of how late policy occurs, since it enables negative abatement (considering biomass gasification for H_2

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[75] Industry was not considered because results were very similar across all scenarios, as it may be observed in Annex A.

production, which is the case) under such a stringent low carbon policy as defined by the caps.

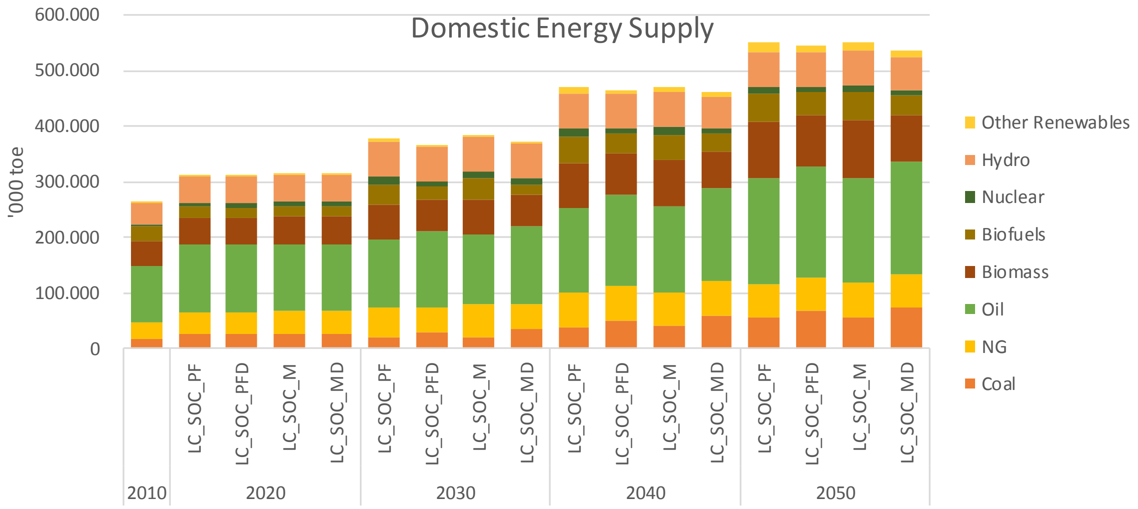

Figure 5-19 – Comparison of domestic primary energy supply between early action and delayed action scenarios discounted at social DR.

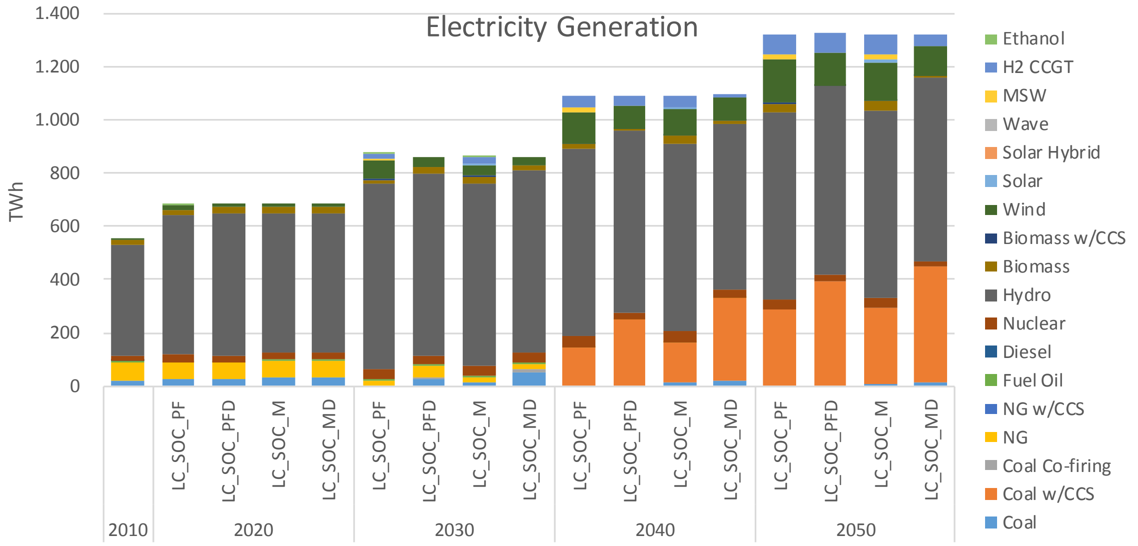

Figure 5-20 – Comparison of electricity generation between early action and delayed action scenarios discounted at social DR.

In the transport sector it is also possible to observe differences between early action and delayed action scenarios in Figure 5-21, since delayed action scenario does not allow the use of ethanol buses in substitution to diesel buses. This seems controversial as the system would be expected to adopt low carbon technologies (biofuel, for example) and it will be discussed in section 5.5.

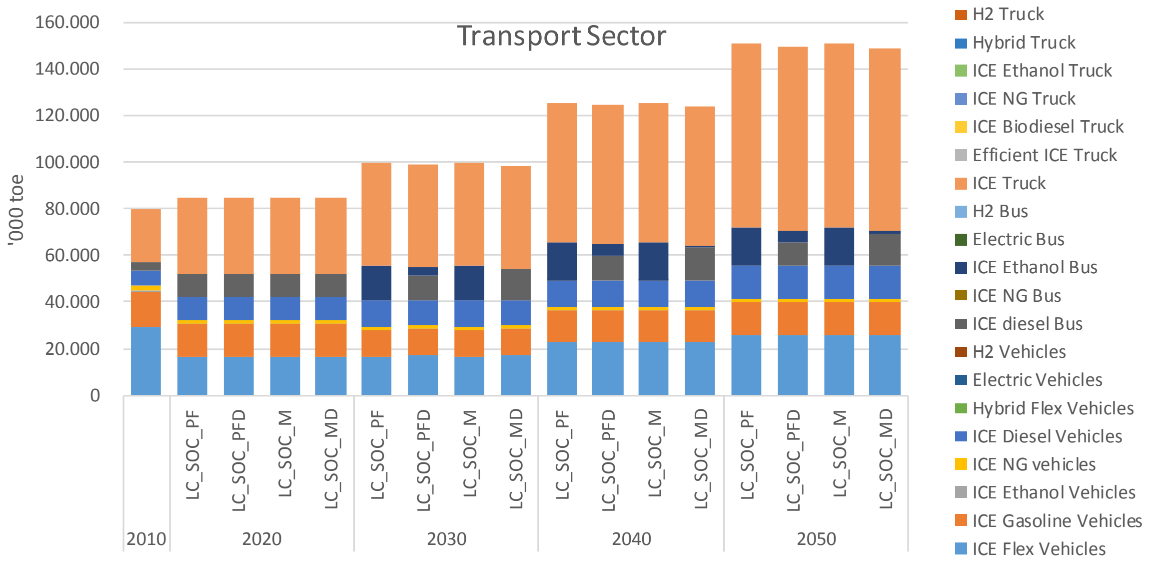

Figure 5-21 – Comparison of transport sector technologies between early action and delayed action scenarios discounted at social DR.

In the CO_2 emissions figure (Figure 5-22) for the social discount rate scenarios it is possible to see the effect of different levels of carbon capture adoption across early and delayed action scenarios. As early action scenario starts capturing earlier, in 2030 through bioCCS, delayed action scenario has a high emission level in this period. It also uses more capture in power sector in later periods in order to compensate the null action of earlier periods and bring CO_2 emissions to the required level. It, indeed, corroborates Figure 5-20 indicating that delayed action scenarios have to rely more in carbon capture technologies to cope with delayed climate policies.

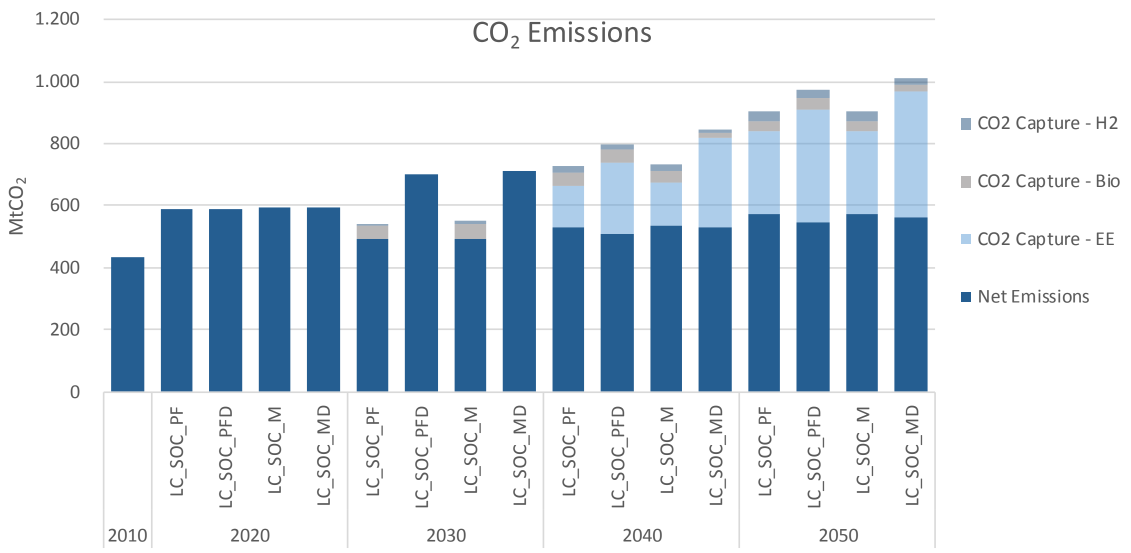

Figure 5-22 – Comparison of CO$_2$ emissions between early action and delayed action scenarios discounted at social DR.
(Note: net emissions correspond to gross emissions minus captured emissions by CCS technologies, when these technologies are adopted.)

Regarding market discount rate scenarios, Figure 5-23 shows that fossil fuels use also fluctuates across scenarios as a function of coal use in the power sector, as it is adopted in large scale mostly in pulverized coal (PC) power plants with CCS. Electricity generation figure (Figure 5-25) shows the same trend of social discount rate, with coal power plants with CCS playing a bigger role in delayed action scenarios, in which either PC and IGCC power plants with CCS are adopted. Meanwhile, renewables have a greater share in early action scenarios. This indicates that as delayed action scenarios require more rigorous actions to cope with a more stringent cap restriction, it enables more advanced technologies to become viable since they would allow to reduce emissions significantly. Thus, this justifies the dislocation of renewable sources for CCS technologies (fossil, bio and H$_2$) in delayed action scenarios when compared to early action scenarios.

Biofuels supply is higher in early action scenarios because it is used in flex fuel vehicles in substitution to blended gasoline. In turn, biomass use seems to be higher in early action scenarios because of the adoption of biomass gasification for hydrogen generation, which is used in combined cycle gas turbine units in the power sector.

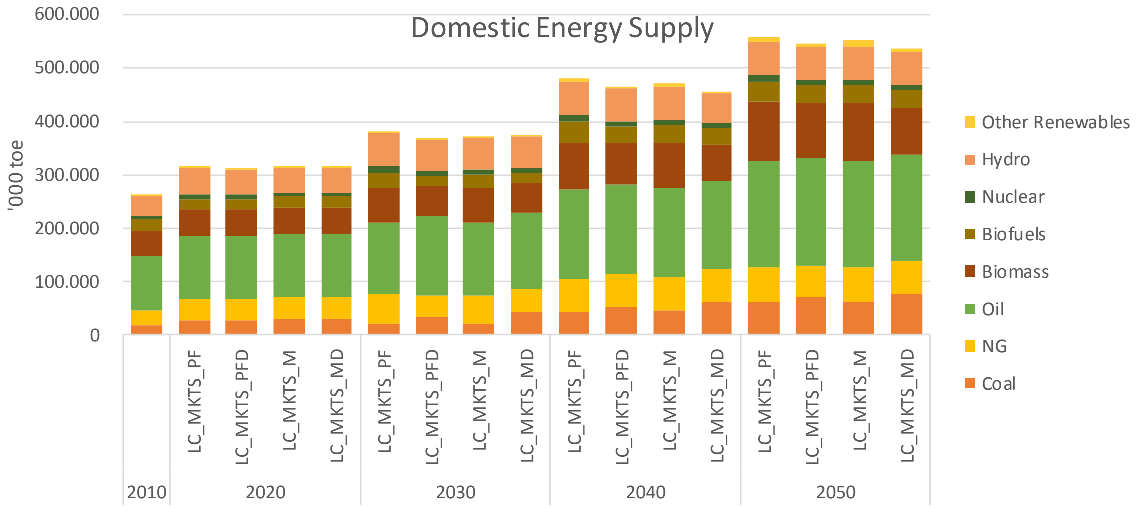

Figure 5-23 – Comparison of domestic primary energy supply between early action and delayed action scenarios discounted at market DR.

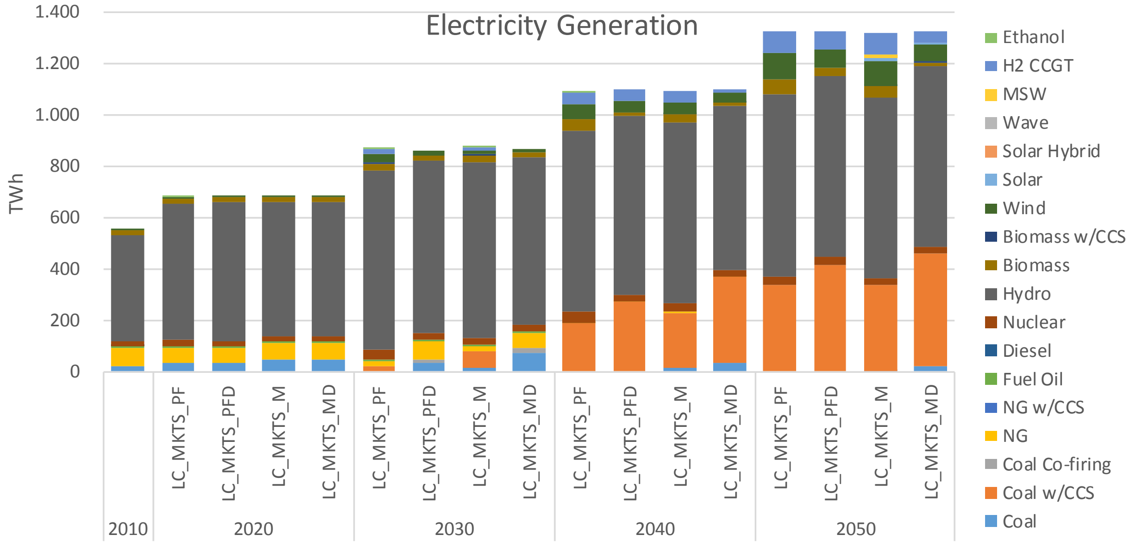

Figure 5-24 – Comparison of electricity generation between early action and delayed action scenarios discounted at market DR.

On the other hand, transport sector presents a different behavior, keeping the participation of technologies relatively constant between early and delayed action scenarios, as show in Figure 5-25. However, detailed results show that flex fuel vehicles consume more ethanol, displacing gasoline, in early action scenarios, as mentioned before. Hence, one can infer that more ethanol availability is higher when the least cost option to mitigate is not fossil CCS in the power sector. This will be better discussed in section 5.5.

Emissions figure with market discount rates, in turn, also present the same trend of social discount rate, with early action scenarios starting to mitigate earlier, but delayed action scenarios mitigating more in later periods to compensate for the late effort (Figure 5-26).

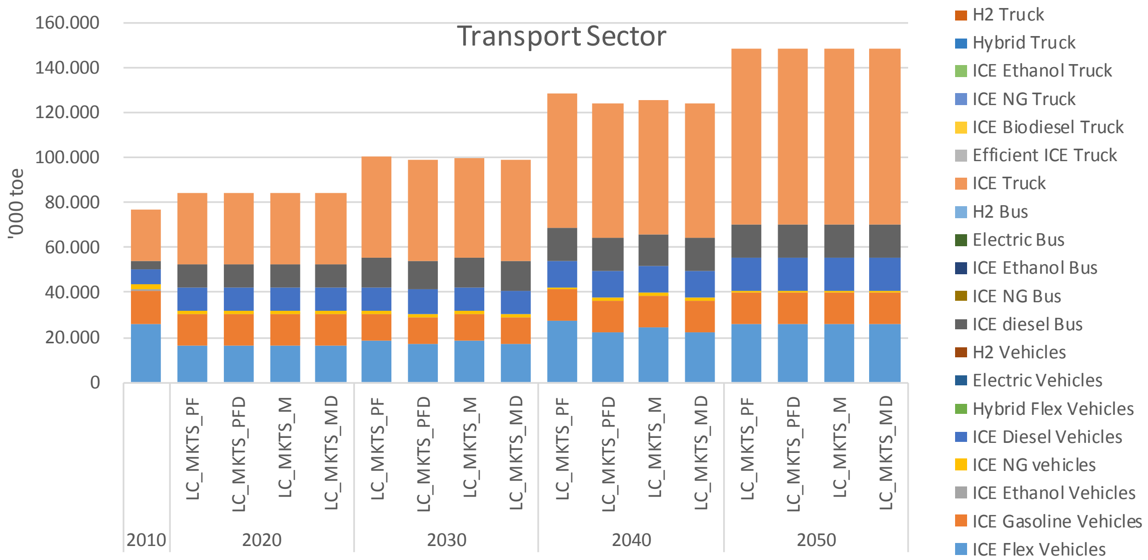

Figure 5-25 – Comparison of transport sector between early action and delayed action scenarios discounted at market DR.

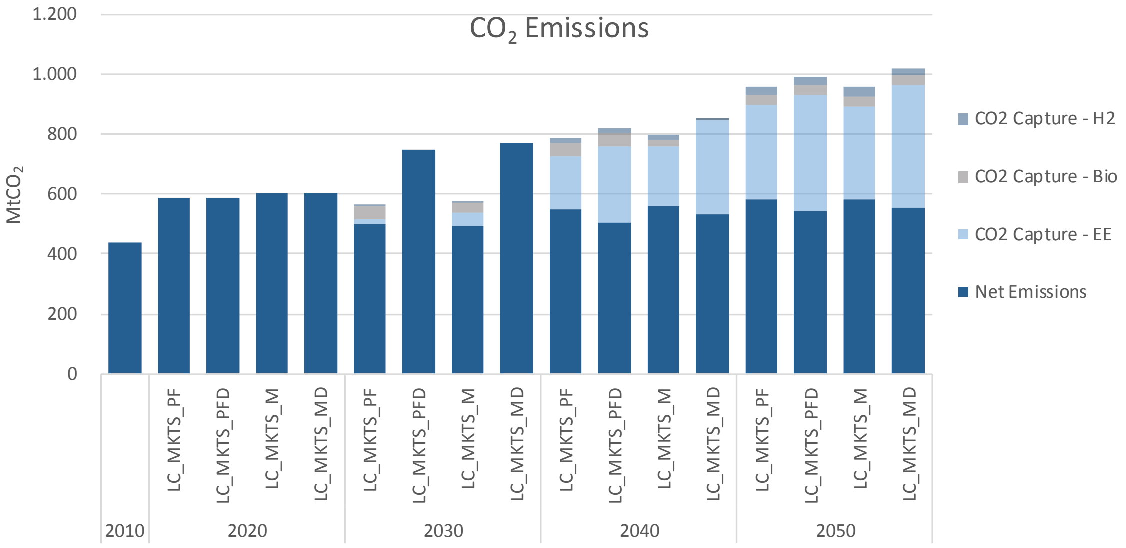

Figure 5-26 – Comparison of CO$_2$ emissions between early action and delayed action scenarios discounted at market DR.
(Note: net emissions correspond to gross emissions minus captured emissions by CCS technologies, when these technologies are adopted.)

Once more, at declining discount rates domestic energy supply seem to have a higher participation of fossil fuels in delayed actions scenarios, although Figure 5-27 shows that the difference between early action and delayed action are small. As fossil fuel share is smaller than in the cases of other discount rate taxes, renewable sources usages are higher as may be observed not only in domestic energy supply, but also in electricity generation figure (Figure 5-28) and transport sector figure (Figure 5-29)[76].

Although the same trend as other discount rates are presented regarding coal power plants with CCS and renewable sources, it should be noted that CCS level in electricity sector is significantly smaller, which is in line with what was discussed in section 5.2 and is due to discount rate choice. The most prominent difference, however, relies on the transport sector, that adopts ethanol ICE trucks in substitution to conventional diesel ICE trucks at different levels in early and delayed action scenarios. Indeed, ethanol buses are more adopted in early periods than in delayed periods, especially in perfect foresight scenarios. In delayed action

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[76] Annex A also shows relative figures, for reference.

scenario with myopic vision there is also the use of more efficient diesel ICE trucks, which can be explained by the integration approach of the model: more coal power plants with CCS usage in electric sector tend to reduce availability of renewables, as occurs at social discount rate taxes.

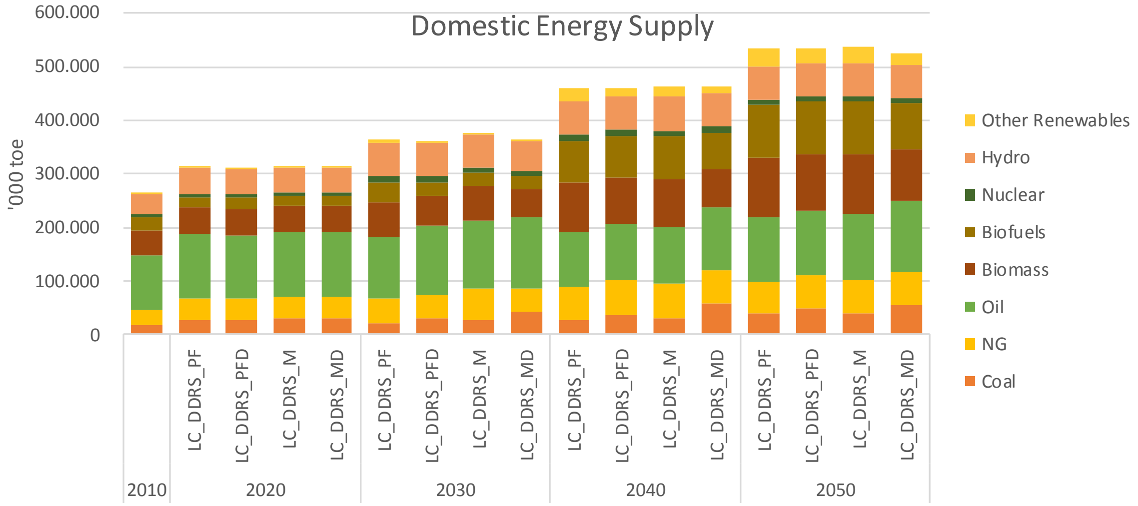

Figure 5-27 – Comparison of domestic primary energy supply between early action and delayed action scenarios discounted at declining DR.

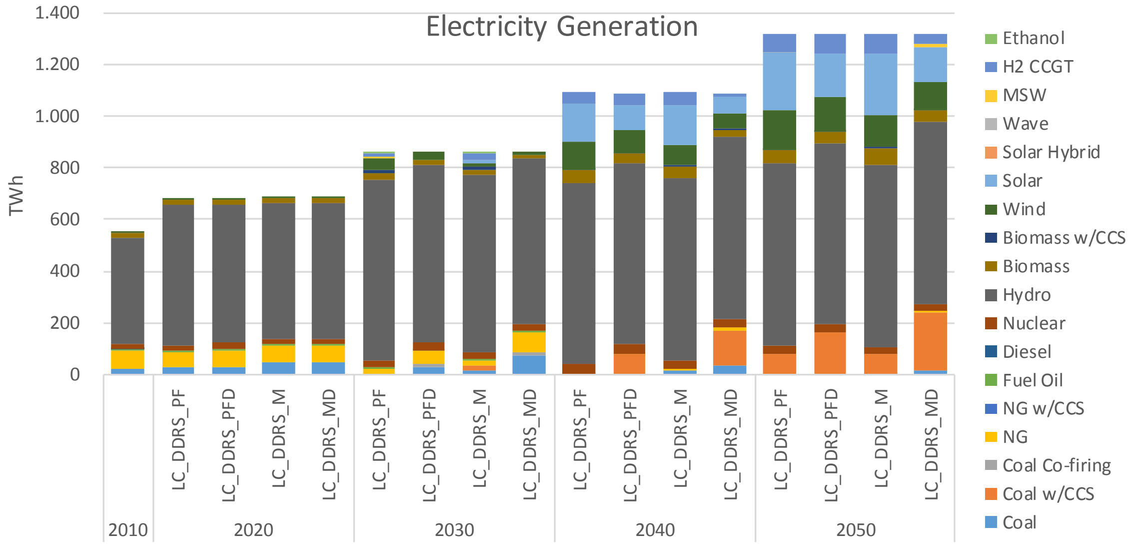

Figure 5-28 – Comparison of electricity generation between early action and delayed action scenarios discounted at declining DR.

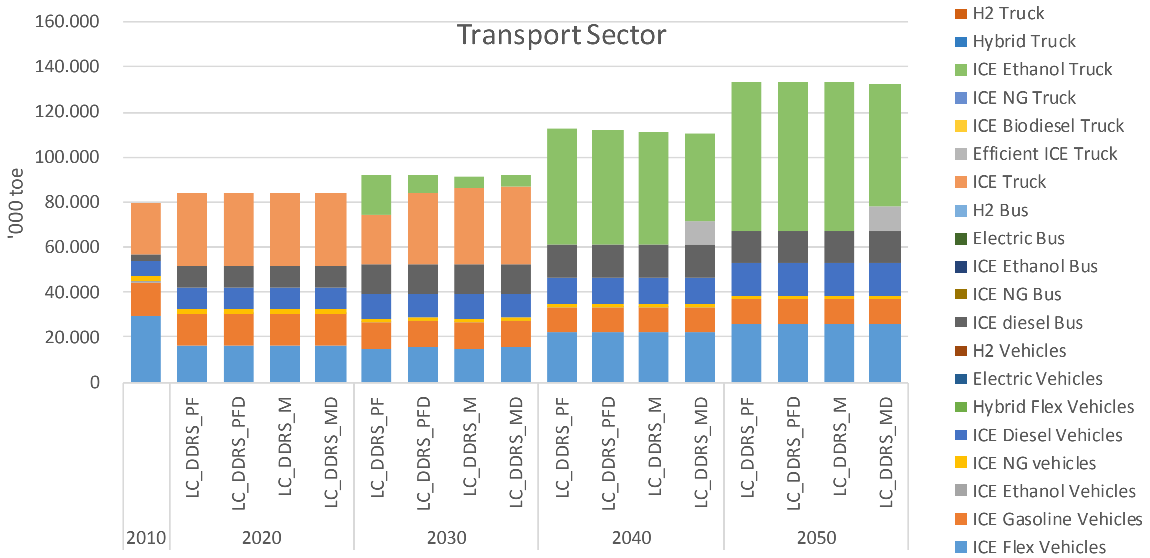

Figure 5-29 – Comparison of transport sector between early action and delayed action scenarios discounted at declining DR.

Regarding CO_2 emissions at declining DR, the trend is similar to other discount rate cases, as can be seen in Figure 5-30. However, CO_2 emissions figures also show that CCS technologies in declining discount rate scenarios are adopted in a lower extent than in scenarios with other discount rates. This is due to the trend of declining discount rate results, since they present lower levels of primary energy supply and they rely more in renewable sources, such as ethanol, wind and solar to mitigate and, consequently, they are less carbon intensive.

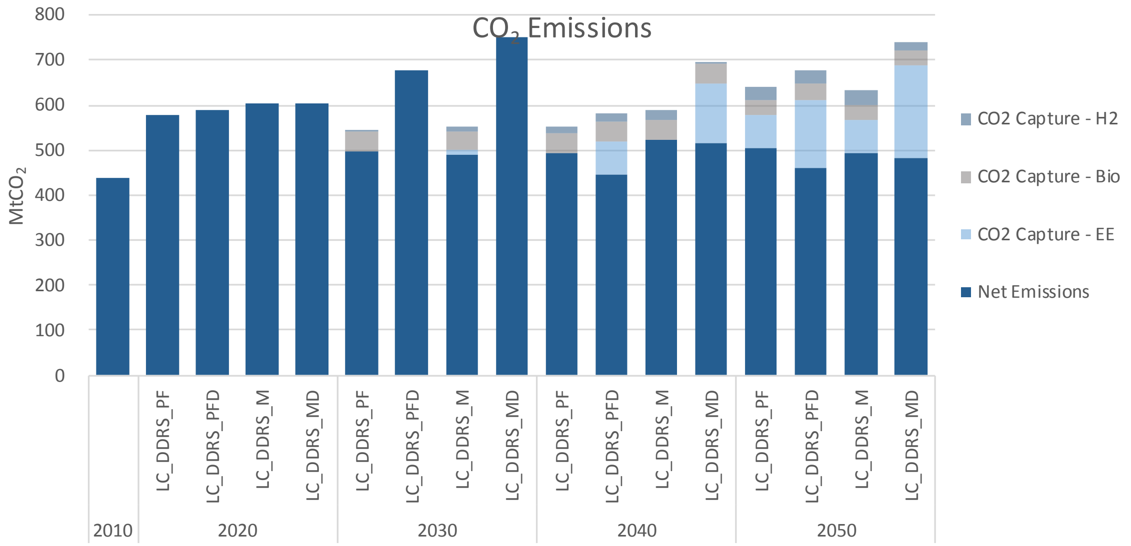

Figure 5-30 – Comparison of CO_2 emissions between early action and delayed action scenarios discounted at declining DR.

(Note: net emissions correspond to gross emissions minus captured emissions by CCS technologies, when these technologies are adopted.)

5.5 Discussion of Results

The results exposed in previous sections of this chapter focused on specific aspects of time preference and practical impacts of each approach (distinct discount rates, perfect foresight versus myopic, early versus delayed action) on Brazil’s energy system could be identified.

Main findings show that market discount rate scenarios promote a more carbon intense matrix. Moreover, under low carbon policies, these market discount rate scenarios rely heavily on carbon capture technologies. On the other hand, declining discount rate scenarios are the ones with highest share of renewable resources in all low carbon scenarios, keeping the trend observed and explained in the base cases analysis. Consequently, emission levels of declining discount rate scenarios are the lowest among the base cases and the set of market discount rate scenarios is the one that has to struggle the most with carbon capture technologies when climate policies are enacted.

Findings also show that a myopic vision regarding climate change mitigation incurs in greater reliance on fossil based electricity generation that is retrofitted with CCS units, instead of early adoption of renewable sources in this sector. Similar effects are caused by the delayed action of committing to mitigation goals, since the main technology adopted to compensate, in the long-term, the inaction of short and mid-term is the CCS technology.

It is possible to observe from the results that carbon capture in the electricity sector is the most adopted capture technology across scenarios, although bioCCS also plays a relevant role in basically every low carbon scenario. The reason to explain that relies not only on cost, as bioCCS linked to ethanol production is not an expensive carbon capture technology especially in Brazil, where carbon is captured at high concentrations from ethanol production through fermentation (Merschmann 2014). It relies also on resource availability, since there is a resource limit for sugarcane, but in the case of coal, there is the possibility of imports[77]. Moreover, the constant annual cap imposed to Brazil's energy system until 2050 constitute a very stringent low carbon policy with no possibility of international and intertemporal trades and this leads to the adoption of very advanced and high cost technologies such as the carbon capture in hydrogen production.

From the discussed above, it is possible to summarize how sources are affected by discount rate and climate policies. Figure 5-31 and Figure 5-32 show radar charts where values correspond to the participation of primary energy resources in low carbon scenarios relative to the primary base case, which is scenario BASE_MKTS (with different market discount rates per sector). Figure 5-31 and Figure 5-32 show results for 2030 and 2050, respectively. It can be observed that other renewables, namely wind, solar and MSW, are very sensitive to carbon policies especially in declining discount rates (in 2050) and social discount rate (in 2030) scenarios. The bigger difference is given in 2030, which indicates that, in 2050, these sources are expanded also in the base cases. Biofuels use is also significantly influenced by low carbon policies especially in declining discount rates in 2050, which is mainly driven by ethanol use in heavy vehicles in substitution to diesel. Crude oil, natural gas and coal sources fluctuate a little across scenarios, with natural gas increasing its

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[77] Constrained by harbors' capacities.

usage in 2030 and coal reducing its usage in the both periods (2030 and 2050) especially in declining discount rate scenarios. Although coal use is reduced in low carbon scenarios, it plays an important role in mitigation with CCS technologies, as will be discussed.

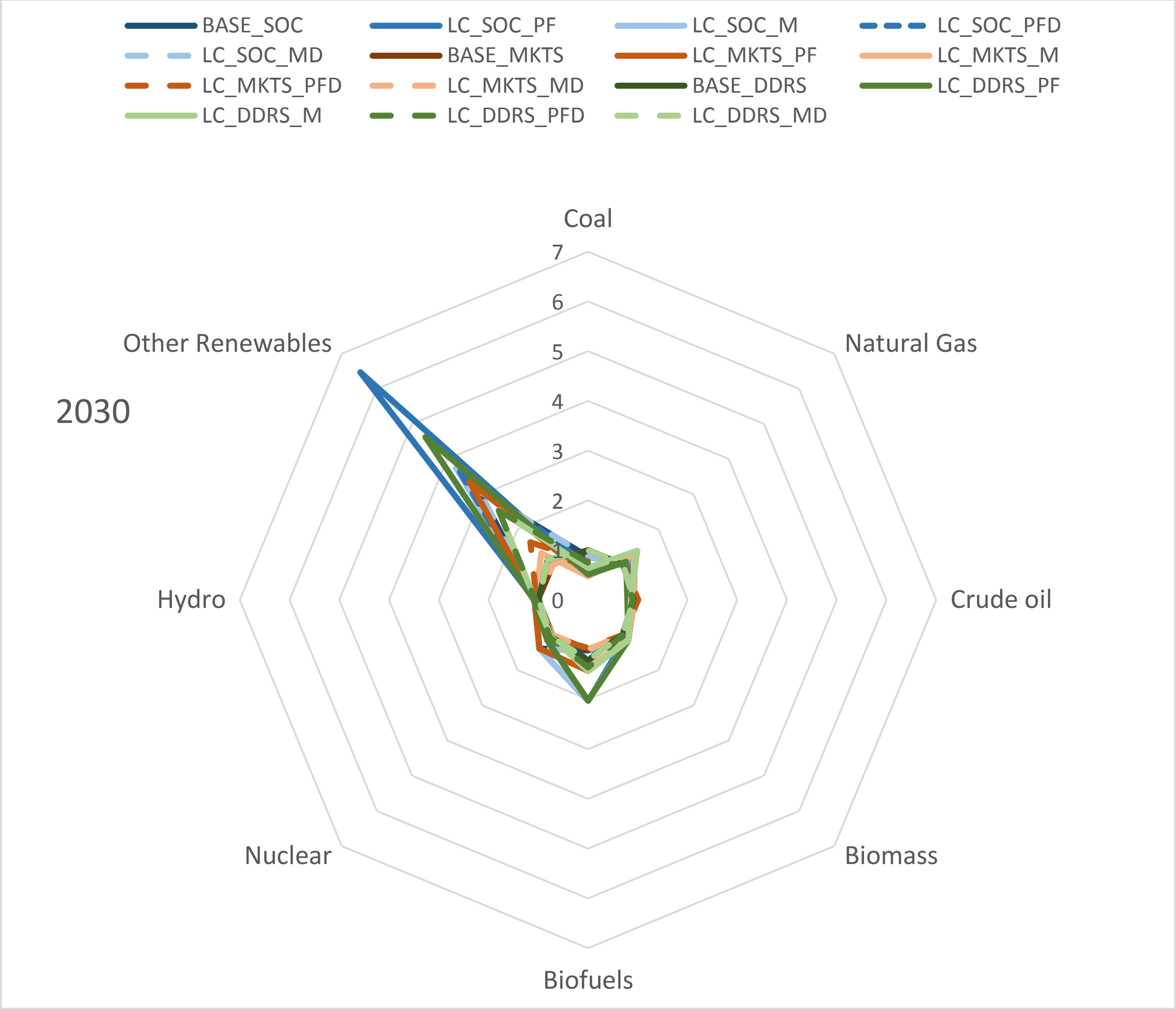

Figure 5-31 – Participation of primary sources across low carbon scenarios normalized to respective base cases – 2030.

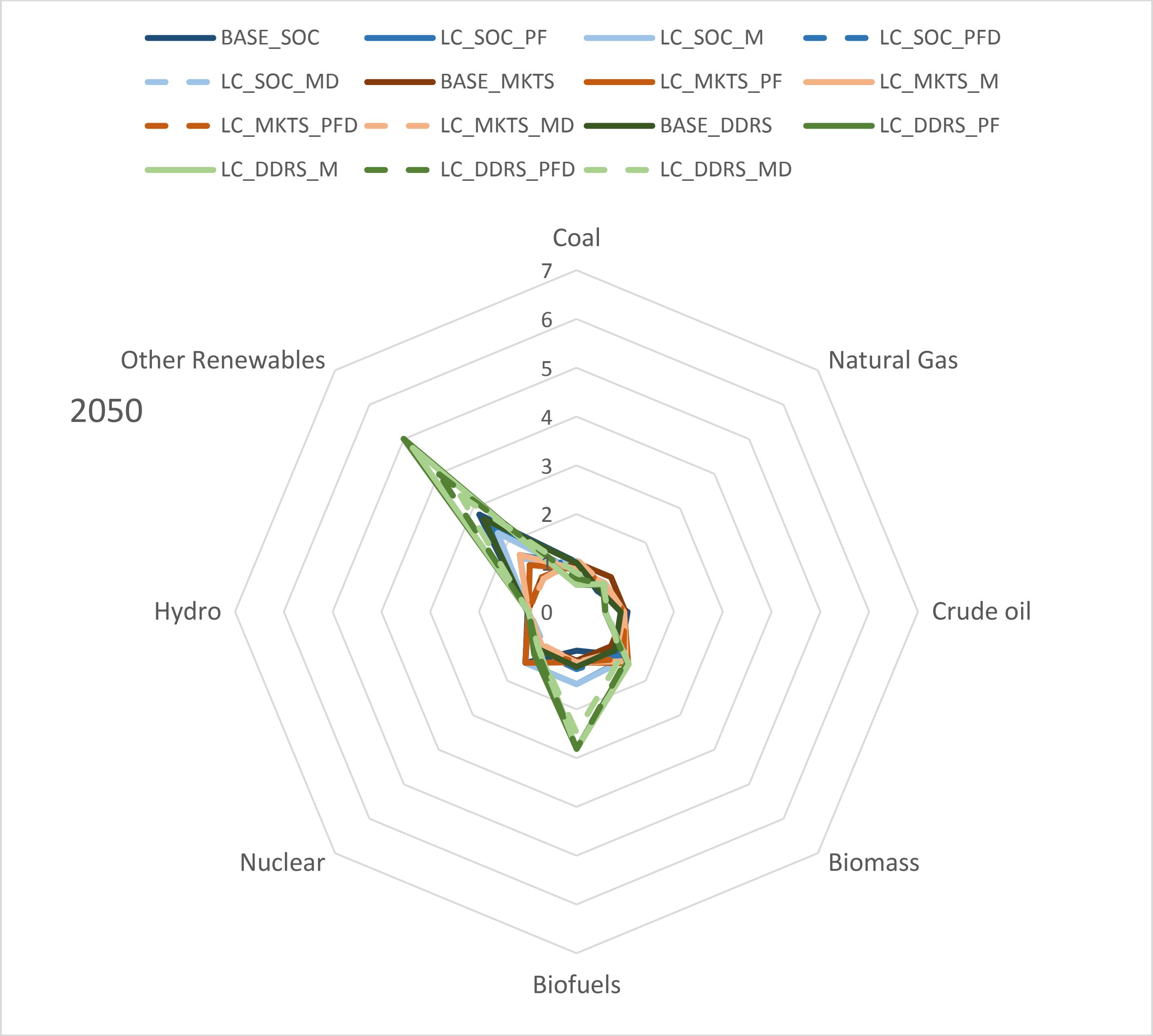

Figure 5-32 – Participation of primary sources across low carbon scenarios normalized to respective base cases – 2050.

From the radar chart exposed in Figure 5-33 it is also possible to observe the importance of different types of CCS technologies across scenarios. The scale in the chart is based on the percentage abated from gross cumulative emissions in each scenario. It can be inferred that fossil CCS is an important source of mitigation especially in market discount rate scenarios, which is a natural consequence of the fact this is the most carbon intensive and fossil based scenario. It can be responsible to up to 16% of abated emissions. BioCCS has a relatively constant role in scenarios, but its participation is significantly inferior, since this technology may abate up to 4% of emissions. Lastly, capture in hydrogen generation technologies are adopted only in cap scenarios since they are very restricted and Figure 5-33 indicates its participation is minor relative to other CCS technologies.

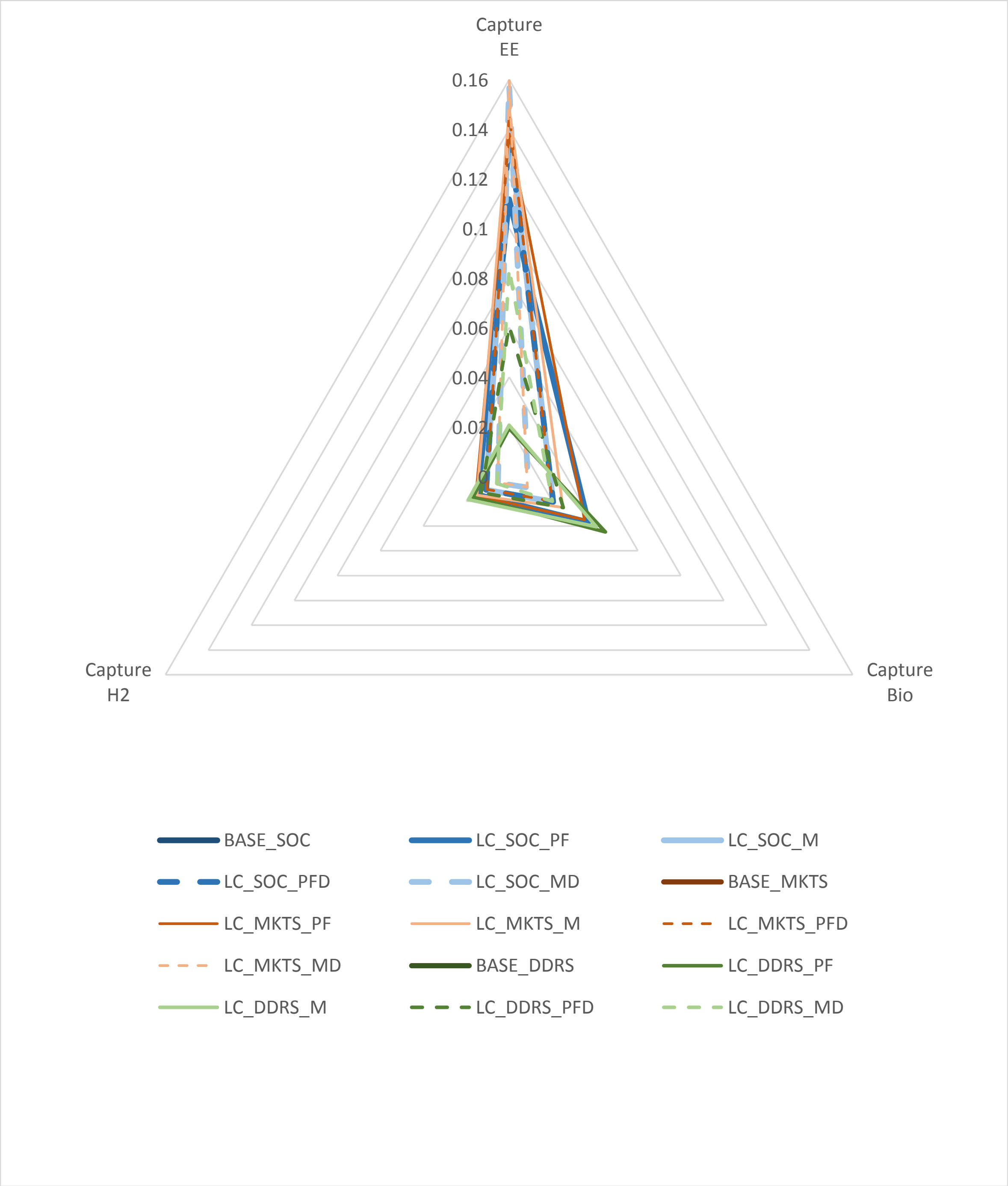

Figure 5-33 – Share of abated cumulative emissions through CCS technologies across scenarios.

Therefore, it is possible to conclude that scenarios subject to low carbon policies, indeed, may evolve differently when subject to different perspectives of discount rates. Although the use of some sources are not very influenced, other sources, like renewables such as wind, solar and biofuels and also CCS technologies may vary significantly depending on the discount rate adopted. This has important implications for policy design, since the technology mix that one might find more cost-effective when attempting to mitigate emissions might vary depending on the approach taken. Clearly, private agents would follow a different transition than the one expected by public agents or by ones who believe that future generation welfare should be valued as much as current generation welfare. Thus, to bridge that gap and to bring different agents to the same perspective energy systems modeling is important as a tool to foster a low carbon pathway.

The comparison of base cases BASE_MKTS, BASE_SOC and BASE_DDRS show that given a no carbon policy, high discount rates tend to favor fossil based technologies over renewable technologies, as shown by the fact that scenario BASE_MKTS is the one with highest use of fossils, especially natural gas; and it is also the most carbon intensive scenario. Meanwhile, even though there is no environmental constraint that constitutes a stimulus to usage, wind energy, solar energy and MSW energy are used in BASE_SOC and BASE_DDRS scenarios. It is also important to notice the significant substitution of oil products by biofuels that can be noticed in BASE_DDRS.

The discounting effect on the results is related to the value of investment cost and operating cost of technologies. As highlighted in chapter 3, conventional technologies have lower upfront costs, but higher operating costs especially due to fuel costs. These types of technologies tend to be favored by a high discount rate, which will discount more operating cost during their lifetime. On the other hand, renewable technologies have high upfront investment costs and low operating costs during their existence, being less favored by high discount rates that put a lower weight on their operational cost savings. It is also interesting to notice that a declining discount rate could indeed favor these technologies, when compared to a constant low discount rate (like a constant social rate). This happens because it would discount more the high investment cost of these technologies and discount less their high lifetime cost savings, making them more attractive. Comparatively, running costs would be less discounted, impacting negatively more conventional technologies than renewable ones. That indeed can be seen in scenario results, especially with the insertion of the solar power technology, mainly CSP, in scenario BASE_DDRS. This became viable even though CSP is a technology with a significant high investment cost[78] and it is installed from 2040: since it has no operating cost to be discounted, it was made feasible when compared to fossil based technologies that would have their operating costs little discounted.

These results are somewhat adherent with what was discussed in item 3.2 of chapter 3: as declining discount rates attempt to deal with uncertainty of distant future periods and to avoid underestimation of the value of future generations, they tend to favor technologies that should incur in less losses (which the model sees as financial losses through increased costs, as it is based on cost of technologies) in the future, not compromising the welfare of future generations. These technologies are the renewable low carbon technologies, such as wind and solar power conversion. They, indeed, do not exhaust resources and they are very cheap to operate, which is perceived by the model as cost effective in the long term when low discount rates in the future are applied. The constant social discount rate is also an approach that aims at dealing with valuing properly the well-being of future generations, although it may also consider the marginal social rate of return that reflects riskless private investments. It also results in scenarios with a good share of renewables, which corroborates the fact that these sources are more suitable to foster a cost-effective energy system towards the climate change issue.

On the other hand, market discount rates reflect the perception of private agents regarding market conditions, access to capital, risk, etc. These agents have as the main focus the maximization of profit and, as a consequence, they have a high preference for the present. For these agents, the least cost pathway is driven by technologies that reinforce the existing technological configuration, that have sunk costs, economies of scale and learning experience. Scenario results show that cost-effective technologies under that perspective are fossil-based, mainly coal and natural gas resources, which leads to a carbon intensive energy

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[78] Approximately US$ 7,000.00/MW from 2035 on.

system when no carbon policies are applied and relies a lot in carbon capture technologies when a mitigation policy is put in place. This, in fact, reinforces the technological lock-in especially in the medium-term and incur in higher costs for the system.

It also worth noticing that not differentiating the distinct access to capital levels of Brazil's economic sectors has also an impact in results. Bringing all sector to a 15% discount rate level equalize the existing market failures of different sectors and indicates that they have to overcome similar barriers to be adopted by the system, which is not true. The result of these premises was an even more carbon intensive matrix, primarily based on coal resources. It can be said that this is an expected outcome, since fossil-based, especially coal-based, technologies tend to be cheaper technologies because they are fully dominated and have reached a long-way in their learning. Hence, under the same level of access to capital than other technologies, it is natural that they prevail.

It is interesting to note, therefore, that the premise underlying the choice of the discount rate to be adopted when evaluating a project might constitute itself a promoter of a low carbon energy system, since some approaches favor low carbon options in substitution to conventional fossil technologies. The social and declining discount rates lead to mitigation even though no carbon policy is applied and a stimulus (through public policy instruments) for investors to discount at these rates could be given in order to help fostering a sustainable future.

It is known that elements that deviate private from social perspective are related to market barriers to adoption, which includes imperfect markets, asymmetry of information, hidden costs, risk perception, etc. In that sense, policy instruments to be used in order to converge those perspectives should have as main effect the elimination of those barriers, which would bring private market discount rate to social discount rate. The main focus in this case is to bridge that gap in order to overcome asymmetries that cause a divergence of private and social perspectives and might lead public policies towards the wrong direction and unexpected results. In that context, energy policy instruments may have an important role in low carbon policy and may be combined with carbon market mechanisms in a way to promote an energy transition to a low carbon economy through the broad adoption of renewables, in accordance to model results under a prescriptive perspective.

It was discussed in chapter 2 that energy instruments may be of different natures, such as economic, R&D-related, regulatory, etc. In all spheres there are instruments that could indirectly affect valuation parameters chosen by investors, including the discount rate. Hence, the viability of specific projects is improved, constituting a promoter of specific technologies, such as renewables like wind and solar. Among them, it might be cited performance-based incentives, such as feed-in tariffs that will fix the energy price, and, then, will reduce the risk of the project. Also, grants, tax incentives and subsidies are also economic instruments that influence the costs for consumers and for producers, contributing to the market creation and to the elimination of economic barriers[79]. These actions create a favorable condition for the development of new technologies, since they deal with issues of costs, but it is important to highlight that they have to be well design to fit current conditions in Brazil. Brazil already has a well-succeeded promotion scheme of renewables through auctions and a feed-in-tariffs, for example, once overlapped with this framework could destabilize the market and raise prices. Also, it is important to notice that currently the country also has some incentives for renewables in place, like the ones instituted by REIDI (Regime Especial de Incentivos ao Desenvolvimento de Infra-estrutura/Especial Incentive Regime to Infrastructure Development), that exempts investors on energy from specific taxes[80] (Ministério da Fazenda 2016a). In that context, the redefinition of the existing framework or the implementation of new schemes should be always well evaluated to avoid doubling incentives or creating unwanted market distortions.

Under this approach of adopting different instruments to promote a low carbon future, it is important to have an adequate framework that will evaluate, plan, implement and audit these actions in order to make them effective and efficient. An adequate institutional framework constitutes a policy support mechanism and it is dependent on specialized

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[79] When the cost of a given technology is superior to the cost of alternative technologies even under optimal market conditions (Muller et al. 2011).

[80] PIS/COFINS: Social integration program and contribution to financing social security, respectively. For details on these, see (Ministério da Fazenda 2016b).

expertise and deep knowledge of technological, regulatory and economic aspects related to the technologies to be promoted and to be phased-out. As this work does not aim at detailing how this institutional framework should be designed, it is worth highlighting, though, that Brazil's existing institutions already play a significant part on different energy-related sectors in Brazil[81] and the experience of these institutions and their members could be availed to properly plan, implement and regulate the instruments here proposed. Moreover, the establishment of a robust scheme to go through all steps of policy instruments execution should help the consolidation of a secure market and the reduction of uncertainties perceived by investors, influencing somehow their willingness to invest.

Furthermore, regulatory instruments also constitute means of reducing uncertainties related to the development and implementation of new low carbon technologies. One approach could be imposing standards on specific issues such as how the produced energy will be sold, i.e., establishing power purchase agreements (PPA). The standardization of contracting should guarantee to producers the terms of their remuneration, encouraging investment (UNIDO 2008). It is important to notice, though, that PPA schemes already exists in Brazil, the electricity sector as example. Moreover, the adequate distinction of PPAs according to the resource used to generate energy might bring some leverage to specific technologies, promoting their development over other. This, thus, could constitute a mean of fostering a low carbon transition through defined sources and technologies.

The need for skilled and trained labor is important not only for regulating properly the promotion framework, but also to foster the technical development of mitigation options under the transition towards a low carbon future through renewables, for example. In this sense, another instrument, educational wise, is the creation of capacitation schemes in order to generate trained labor ready to work on the development of technologies, which would improve the learning process and accelerate cost reductions. These capacitation schemes could be related to collaborations with international institutions that could contribute with their expertise, to the foundation of specific graduate and undergraduate programs with focus

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[81] It could be mentioned the regulation agencies of electricity (ANEEL) and of oil, gas and biofuels (ANP) as examples.

on certain technologies (such as renewables) and to the installation of adequate laboratorial infrastructure that could help training this labour (Muller et al. 2011).

Under this context, this is directly linked to the deployment of an effective research and development promotion scheme, which should foster the economic viability of new technologies. It is a challenge to deal with immature technologies since they need a joint effort of technology-push supported by governments and of market-pull promoted by businesses (Oliveira et al. 2016). As government usually acknowledges that it is responsible for the early and high risk R&D, it supposes that private sector will take over commercialization. However, it is common that private agents keep themselves wary about investing in new technologies and, thus, neither government or private sector take the lead, which result in a lack of funding, situation commonly called “the valley of death”. Hence, creating ways to bring together public and private funding mechanisms is important to foster low carbon technologies (Muller et al. 2011).

The deployment phase of a given technology varies from one place to another, with different barriers presenting different levels of relevance. To overcome them, Muller et al. (2011) mentions that it is important to benefit from international experience and learning, which could be made by establishing collaborations among national and international institutions. However, some barriers are particular to specific markets and this should lead to an effort of adapting technologies to their conditions. In the case of Brazil, for example, wind turbines could be adapted to resist salinity levels of North-east coast regions, where wind potential is high. In all cases, adequate funding schemes should be put in place in order to enable investments in research and development, leading to the learning process which results in the reduction of costs and risks.

Moreover, a mandatory regime could also be adopted, obligating investors to evaluate their project under specific pre-defined parameters, such as discount rates. This approach could be adopted especially in regulated markets, such as the electricity. In fact, in this case, discount rates are already indirectly influenced by the establishment of the ceiling price of auctions and of the calculation methodology for energy production. However, it would be important to assess the impacts of such a policy on investments in different energy-related sectors, since this could be perceived as an action that could lead to financial losses to private agents.

It is important to highlight that this discussion aims at summarizing options that could be considered as policy instruments that could lead Brazil's energy system towards a low carbon future. Moreover, the evaluation and choice of the best instrument and possible impacts, co-benefits and weaknesses are not in the scope of this thesis, since it would require a deep analysis that goes beyond answering the questions this thesis seeks to. However, this type of work could constitute a next step for this thesis and it will be listed as a proposition of future work in chapter 6.

Regarding scenarios with timing issues related to technological lock-in and starting moment of mitigation efforts, it can be inferred from results that lock-in effects may change technology portfolio in some periods of the time horizon when agents are myopic in relation to climate change policy, either by retarding the penetration of new technologies in the first periods of policy (such as happen with biofuel ICE engines in the transport sector) or compromising the decommissioning of conventional technology (such as coal power plants without CCS). Agents may lack long term vision and disregard any possibility of engaging in low carbon actions before commitments are made, therefore having behavior close to business-as-usual and not investing in low carbon technologies. However, if a low carbon transition is still implemented, it incurs in higher costs to the system, as it will be discussed.

Moreover, low carbon constraint is put in place in 2030 and in 2040 (in delayed action scenarios), which means that more than half of time periods in myopic vision scenarios present business-as-usual behavior. In that context, it is indeed expected a more stringent lock-in effect related to fossil fuel technologies, as observed.

As technological lock-in effects are led by microeconomic effects at firm and consumer level decision-making (barriers to adoption[82]), it is important to highlight the path-

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[82] For the emergent technology.

dependency phenomenon, as discussed in section 3.3.1 and mentioned in Unruh (2000); Foxon (2002); and Perkins (2003). This is a result of positive feedbacks between technological infrastructures and organizations that create, diffuse and employ them (Unruh 2000). It is a complex system that includes not only technological aspects and cost issues, but also norms, standards, values and behavior.

However, for the purpose of this thesis, it was adopted a minimum cost based model and it does not perceive these web of institutional and behavioral issues associated with technological lock-in. The result is obtained by fixing first periods with no carbon policy to baseline scenarios results profile and then the remaining periods (with implemented low carbon policy) are optimized. The fixation of periods with no carbon policy consist in a simple approach that should reflect the lock-in resulted from the combination of different classes of increasing returns (scale economies, learning effects, adaptive expectations, network economies) of incumbent technologies, mainly fossil fuel-based. Hence, scenario results should give insight on the feasibility of achieving a low carbon transition when technology mix of the energy system before carbon policy reflect the lack of precautionary action towards climate change under the minimum cost approach. As a simple approach, it might underestimate real lock-in effects, since elements such as agency and interactions of different institutions are not inputs to the model[83].

In that sense, interpretation of results should be strictly linked to the technology composition of scenarios and scenarios' costs, which should entail some insight on cost of policies. Results show that, as all low carbon scenarios are feasible, it is possible to conduct a low carbon transition in Brazil's energy system under the time horizon considered, even though choices related to time preference and anticipation of mitigation might not favor it. However, impact on technological pathway is not ignored, as it is possible to notice that fossil CCS becomes really relevant both in myopic foresight and delayed actions cases, which indicates that the choice of not acting in a precautionary way in terms of mitigation indeed reinforce the carbon lock-in in Brazil through the perpetuation of fossil fuel usage, locking-

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[83] There are today emerging modeling tools with more complex approaches that might be adopted in order to consider these elements, such as agent-based models (Stern 2016). For more information on these class of models, see Novosel et al. (2015); Rai & Robinson (2015); and Ringler et al. (2016).

out other low carbon options, such as renewables in the electric sector and biofuels in the transport sector.

Results obtained somewhat corroborate studies available in literature, such as Vergragt et al. (2011); Perkins (2003); Bertram et al. (2015). Perkins (2003) affirms that efforts to improve technological performance are often focused in specific directions based on past achievements. This is related to the "path dependence" concept, discussed previously. In that context, it makes sense to affirm that it is easier and more economic to retrofit coal power plants with CCS than to install brand new technologies as it is easier to promote technological change incrementally than abruptly. This is in line with model results under stringent low carbon constraints, since it relies heavily in fossil CCS to cope with the emission cap.

Bertram et al. (2015) focused on the discussion of how low carbon policies in the short and medium term might impact long-term transformation pathways based on the analysis of energy-economic models and IAMs, assuming a hypothesis in line with Johnson et al. (2015)'s study. Their results show, indeed, that huge quantities of coal capacity without CCS would have to be prematurely retired between 2030 and 2050 if global warming is to be limited to 2ºC in 2100. Although models considered in this study are global models, and do not analyze the issue at a country level, it still can be said that results converge with the outcomes of this thesis, since in almost all scenarios coal power plants without CCS are either retrofitted or retired. The study also points that, especially under weak near-term policy scenarios, there will be a need to achieve significant negative emissions in the second half of the century through bioCCS. TIMBRA results show a constant participation of bioCCS across scenarios and considers a time horizon no longer than 2050. Hence, it might be interesting as future work to include more distant time periods to confront results with the literature and check how important bioCCS might become in the very long-term in Brazil.

Through the approach of technical innovation systems (TIS), Vergragt et al. (2011) shows that the fossil fuel provision system is heavily locked-in according to different criteria[84] and that fossil CCS might perpetuate that regime, reinforcing the lock-in regime and making it difficult for other technologies to be implemented. Although, as already discussed, TIMBRA do not perceive all the interactions of a TIS, it corroborates the results of these authors, since the model sees as the main option the adoption of CCS in fossil-based power plants. In fact, scenario results show that, especially when low carbon policy is delayed, fossil CCS technology as the main low carbon option to mitigate causes a fossil fuel lock-in even in other sectors, such as transport sectors[85]. The fact that fossil fuels are more used in ICE engines for transport in delayed action scenarios might seem controversial, since it would be expected a greater effort to mitigate in delayed scenarios in order to compensate the inactivity of earlier periods. Nevertheless, TIMBRA is an integrated model and the choice in one sector is affected by the choice in other sectors: the choice of fossil CCS in the electric sector reduces the remaining share for biofuels in energy supply and less ethanol becomes available to the transport sector, which remains using diesel buses. Critical thinking is needed when evaluating this result, since the model may assume a distinct logic of reality. In this case, the choice in distilleries was not driven mainly by ethanol market but by electricity as a byproduct, which does not respect the rationality of this sector in real life.

Regarding costs differences across scenarios, relative cost of carbon mitigation policies might be evaluated based on the normalized total cost of each scenario in relation to their base case versus normalized emissions. Absolute numbers of total cost are very big and hard to compare between scenarios with different discount rates because discounting leads to different magnitude of numbers. Therefore, in the chart we consider for the analysis (Figure 5-34), the three base cases have unitary values and low carbon scenarios' values show in which extent their total cost deviate from their base case value. Similarly, normalized emissions show in which extent carbon emissions are reduced in relation to the base case.

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[84] Heaviness, interrelatedness, legitimation, learning effects and expectation and interests (Vergragt et al. 2011).

[85] Results in section 5.4 shows that more ethanol is used in transport sector in early action scenarios than in delayed action scenarios.

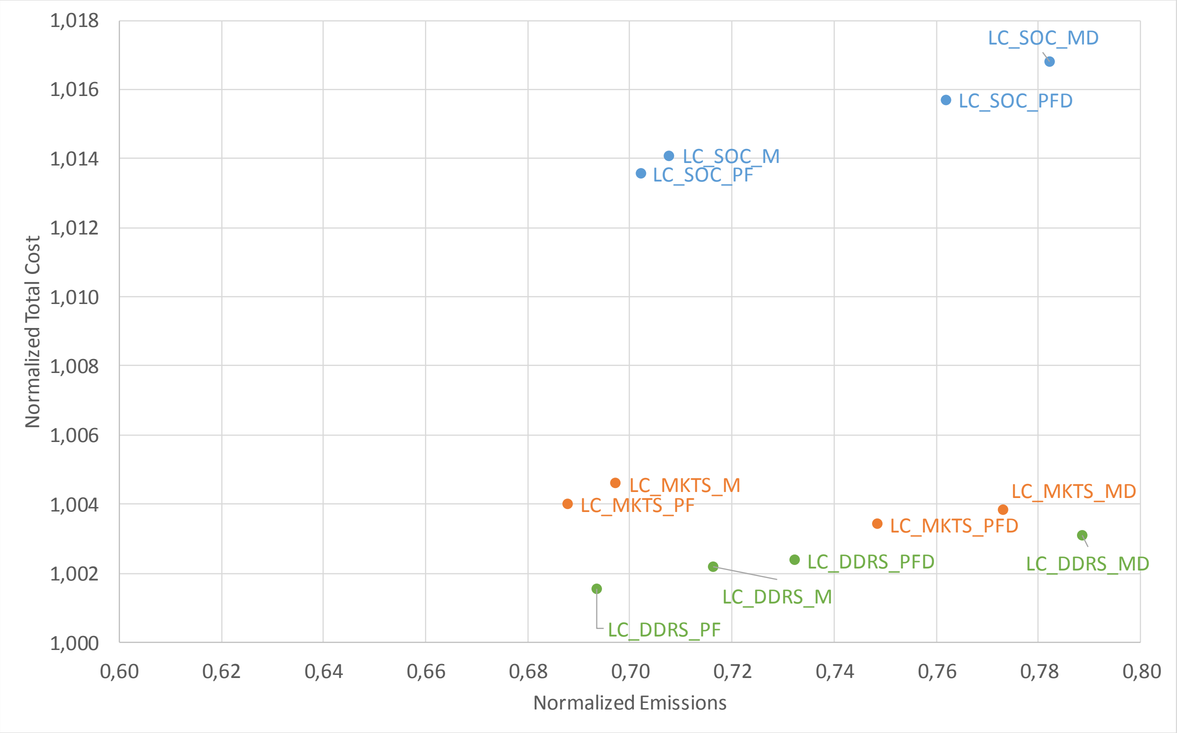

Figure 5-34 – Normalized Global Cost vs. Normalized Emissions of Scenarios.

This approach provides some insight on how low carbon policies might incur in different costs in order to be fulfilled. The first thing to observe is that in all three discount rate cases, myopic foresight scenarios are costlier than early action scenarios, showing that, in fact, there is a measurable impact of technological lock-in on the cost of policies. This results show that the energy system has to struggle more to mitigate when the possibility of anticipation and precautionary action cannot be exercised. Studies like Bertram et al. (2015) and Johnson et al. (2015) also affirm that mitigation costs are higher when the energy system is locked in a fossil fuel based technology portfolio.

When comparing early action scenario results with delayed actions scenarios, it is also expected that delayed action scenarios present higher cost than early action scenarios, since they have to invest heavily in advanced technologies in order to cope with the emission cap in a shorter time. It does, indeed, happen for scenarios with social discount rate and with declining discount rate, but the opposite is presented for market discount rates. This might lead to an erroneous impression that under a market approach it is worth to delay mitigation efforts, but, in truth, this phenomenon may be explained by the discounting effect: market discount rates are usually high and discount more the distant future, giving a less weight to investments incurred in the long-term. In delayed action scenarios, low carbon mitigation efforts are allowed to start only after 2040, and they are highly discounted in model’s cash flows, leading to a final discounted cost lower than early actions scenarios (that have low carbon investments distributed in time periods from 2030).

Finally, it is worth observing that scenarios with social discount rates presented the highest deviation in total costs relative to base case, while declining discount rates presented the lowest deviation. As cap emissions imposed are very strict and allow for high amount of investments in advanced high cost technologies in the mid-term, it is expected different cost profiles under distinct discount rates because the bulk (around 2030 and 2040) of investment is discounted at different rates. Summed up with that is the least-cost technology mix chosen in each case, which incur in different combinations of costs (capital, operational, etc.). Moreover, as these results might indicate that the social approach lead to higher cost of policies, it also brings to light the fact that adopting a discount rate pattern that attributes value to future generation’s welfare might result in economies related to low carbon policy costs.

6 Conclusions

This thesis evaluated the impact of discount rate choice on Brazil's energy system subject to different climate change policies. For this purpose, it was adopted an energy systems modeling tool, TIMES, in which Brazil's energy system was modeled (TIMBRA) in order to be optimized under the least total cost approach and subject to different discount rates and to a set of constraints that should reflect different climate policies.

Discount rates adopted for this study aimed at expressing different perspectives of agents: a social discount rate, a market discount rate and a declining discount rate were considered, the last one with the objective of addressing the intergenerational issue of climate change mitigation by attributing a higher value to future generations. Those rates were applied to Brazil's energy system in order to evaluate least cost technological pathways towards a low carbon future when different sets of carbon policies were put in place. Sixteen scenarios were generated reflecting baseline cases and low carbon policies translated into emissions cap combined with distinct actions regarding mitigation time preference, such as early and delayed action and myopic and perfect foresight, reflecting, hence, different intertemporal choices in terms of investment.

Results inferred from scenarios show that, in fact, discount rate choice may affect significantly the choice and technology mix of Brazil's energy system in the long term. With no carbon policy, market discount rates resulted in the most energy and carbon intensive scenario with high use of natural gas, meanwhile declining discount rates scenario had the lowest energy supply and carbon emissions levels. Natural gas, biofuels and renewables like wind and solar were the sources that varied most from one scenario to another and results indicate that the adoption of declining discount rates tend to favor renewables in the power sector and in transport sector.

It could also be observed that cap emissions constraints as adopted in this thesis based on Spencer et al. (2015) constitute a very stringent low carbon policy that enables advanced technologies such as hydrogen production from biomass gasification. The main advantage of this technology under a low carbon framework is the possibility to capture CO_2 in the hydrogen production and to produce electricity from hydrogen in CCGT power plants. Carbon capture technologies play a significant role across all scenarios, which keep the participation of fossil fuels, such as coal, in Brazil’s mix of sources. BioCCS also play an important part in mitigating and allows for the broad use of ethanol in the transport sector as well.

Moreover, comparison between myopic and perfect foresight show that, indeed, not anticipating climate policies lead to technological lock-in that should cost more to the system. Also, delayed action scenarios with cap restrictions show that the prolonged inactivity related to climate change mitigation may lead to a struggle to mitigate high amount of emissions in less time to compensate and that discount rate choice influence the perception of costs delayed action incurs.

The results of this thesis confirm the hypothesis that discount rate choice has significant influence on technological pathways described in low carbon scenarios. Hence, it may also influence the policy design of low carbon policies to foster a sustainable economy. Indeed, the role of scenario making to orient policymaking is to project possible futures towards sustainability and the exercise of this thesis shows that technological portfolio possibilities given by energy systems scenarios may change substantially according to the discount rate adopted.

Moreover, results show also that agents adopting different discount rates on their evaluations have different perspectives on most cost-effective sustainable futures. This conclusion is important, since it exposes the gap between private and social perspective and evidences the need to combine low carbon policies, such as cap-and-trade and carbon taxes, with policy mechanisms that bridge those perspectives in order to ensure the efficiency of the low carbon policy in terms of technological transitions.

In fact, the adoption of declining discount rates proved to stimulate an energy mix less carbon intensive, with a broad use of renewable sources. This indicates that energy sources such as wind, solar and biofuels are important to foster the welfare of future generations.

Also, this indicates that a low carbon policy may be more effective when this type of discount rate is adopted, since energy use and carbon emissions are lower under this approach.

Although agents in the energy system may not be aware of this, it is possible to broad their vision and incorporate this perspective in their investment decisions through policy instruments, such as financial instruments. Financial instruments may constitute loans at a competitive interest rate, subsidies or fiscal incentives for projects evaluated at a pre-established discount rate. The main objective, in this case, is to reduce the gap between social agents and private agents by eliminating market failures and information asymmetry, and providing access to capital at specific conditions.

As discussed in chapter 2, there are also other instruments that may play that part in combination with climate policies, as of example of instruments to foster research and development (R&D) of developing technologies. This instrument could be adopted to reduce the perception of risk linked to specific technologies by private agents. In this sense, technology diffusion of specific technologies that scenario results proved to be important in a sustainable future could be fostered by stimulating demonstration projects, research programs and by creating niches of consumption.

At last, it is possible to mention that providing information about the importance of evaluating discount rate to be adopted when assessing the viability of projects is also an instrument to promote the convergence of perspective of different agents towards the low carbon energy transition. Also, if diffusing information about this is not effective, the possibility of mandatory instruments, like regulating a specific method of discount rate choice, may also be adopted.

It should be noted, however, that when looking for guidance on the choice of a discount rate, one could find justification for a rate near zero to as high as 20%, as pointed by Harrison (2010). The same author says that the best way to deal with uncertainty about appropriate discount rate is to conduct sensitivity analysis with it. Then, if it reveals that the choice of discount rate is important, i.e., if it changes the sign of project’s net present value or its ranking against alternative projects, then more consideration should be given to it.

In that context, one proposition of future work following the results of this thesis is a more detailed analysis of the influence of discount rates on energy systems by conducting sensitivity analysis of the different discount rates adopted in order to better depict how technology mix changes as discount rate varies. This should help addressing uncertainty of discount rate choice and understanding energy systems behavior towards marginal changes of these rates.

Moreover, this thesis developed a methodology of scenario analysis that should help policymakers on policy design with quantitative information about possible energy transitions in the long term. Although a discussion was made regarding energy policy instruments that could be adopted to help fostering a low carbon transition in combination with low carbon market mechanisms, a deep evaluation related to impacts of these proposition on Brazil’s energy and economic system was beyond the scope of this work. Hence, a natural consequence of this thesis would be a detailed analysis of policy instruments and mechanisms that could address climate change mitigation in Brazil base on scenario results of this work. It is important to note that Brazil has engaged in mitigation commitments, but it has not defined how it will reach these commitments. Thus, now a significant effort should be directed in order to define technological pathways to follow and to establish a policy framework that will enable it.

In terms of modeling structure of TIMBRA tool, there are some enhancements that could be done as a proposition of future work. A better depiction of demand-side abatement options, such as energy efficiency actions, as mitigation options could significantly influence results, since these options reduce demand and relief pressure on energy supply. Moreover, industry sector in TIMBRA is simplified and defined basically by global energy conversion efficiencies per fuel of each segment. A better depiction of technologies in each segment of industry could enhance the response of this sector to climate policies and, hence, make results more robust.

In terms of climate policies, although different types of policies and behaviors were mimicked in this work, it would be interesting to enhance the configuration of cap-and-trade systems in TIMBRA in order to better depict this type of climate policy. To reflect the trade of this systems, it could be established different regions in Brazil in order to reflect a national cap-and-trade system. Moreover, since the climate change is a very long-term issue, considering more distant time periods in the analysis should give some insight on impacts of short and medium-term actions in the long-term, identifying technologies that could have a important hole in the second half of the century.

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Annex A – Results per Scenario

Scenario BASE_SOC

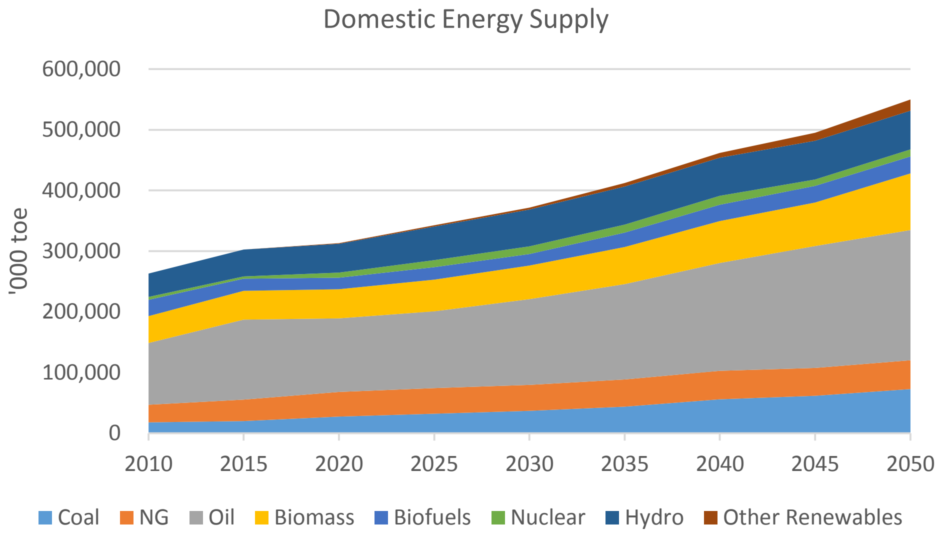

Figure A- 1 – Domestic Primary Energy Supply of scenario BASE_SOC – ktoe

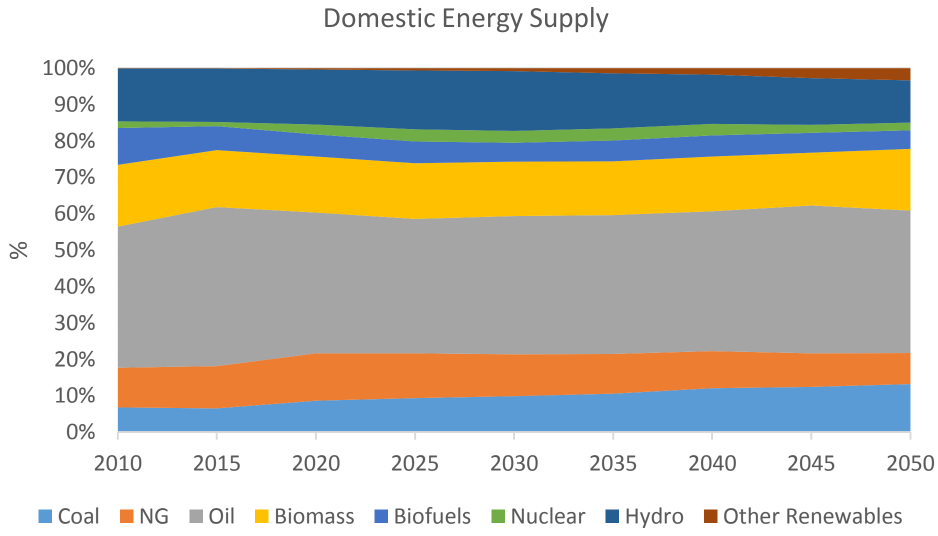

Figure A- 2 – Domestic Primary Energy Supply of scenario BASE_SOC - %

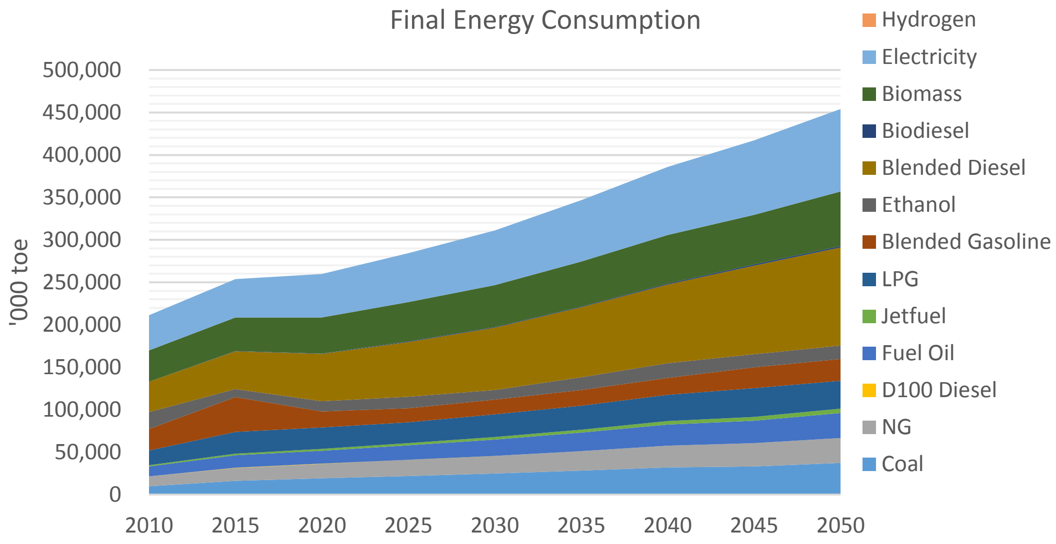

Figure A- 3 – Final Energy Consumption of scenario BASE_SOC – ktoe

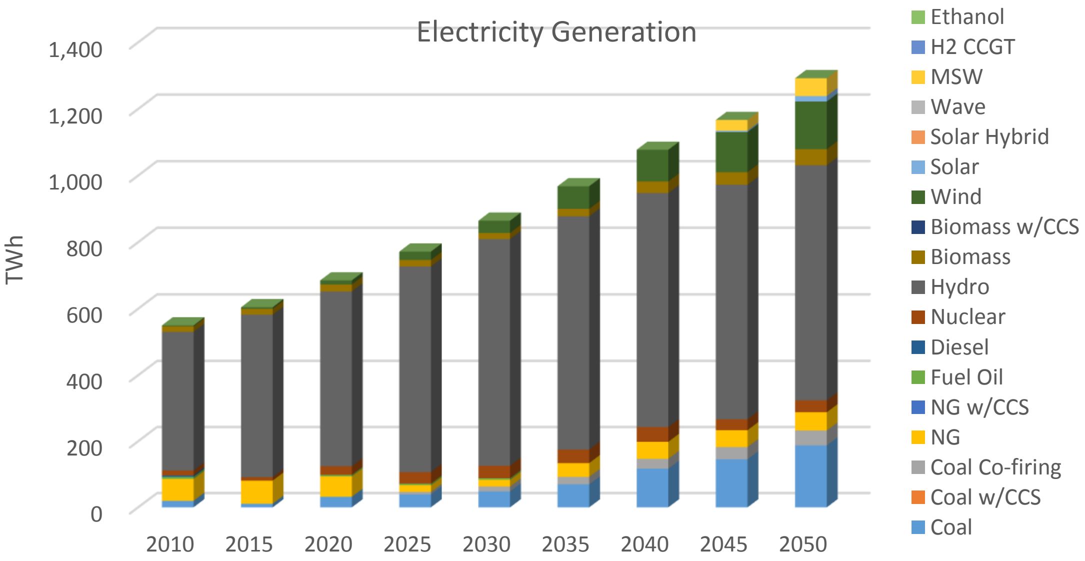

Figure A- 4 – Electricity Generation of scenario BASE_SOC – TWh

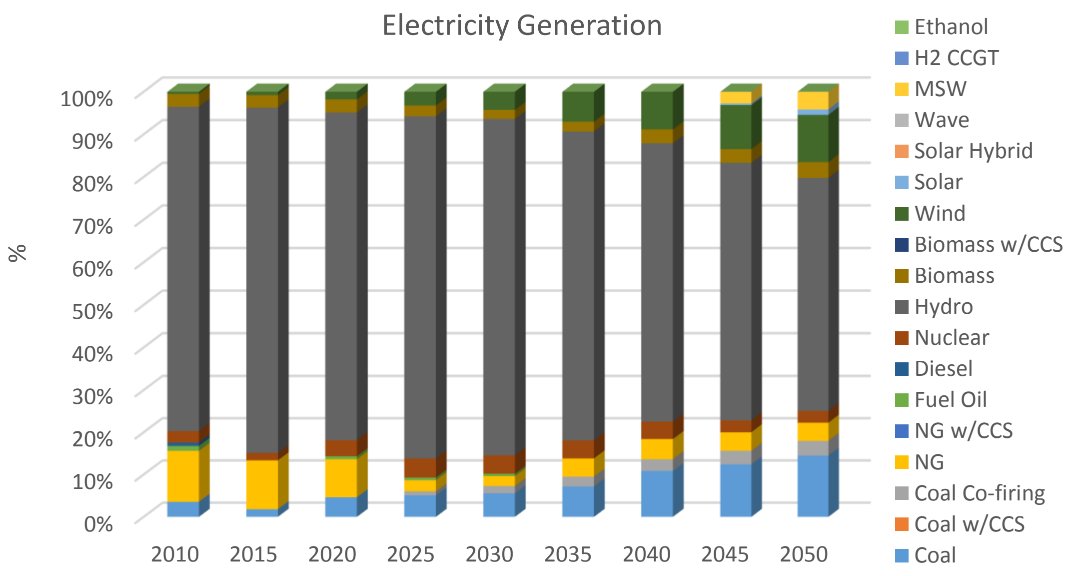

Figure A- 5 – Electricity Generation of scenario BASE_SOC – %

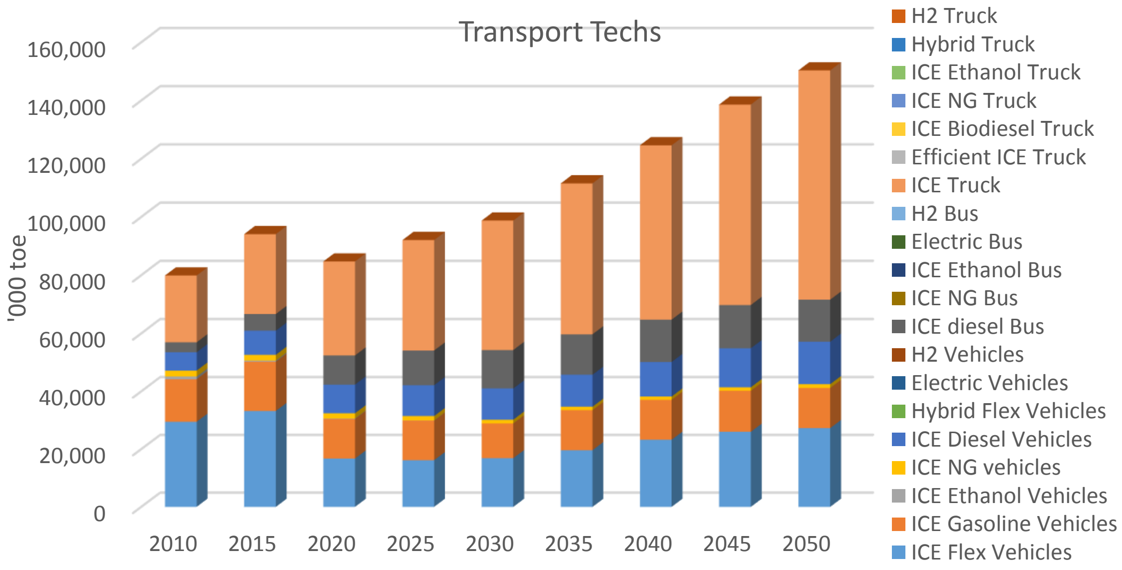

Figure A- 6 – Transport Sector Consumption of scenario BASE_SOC – ktoe

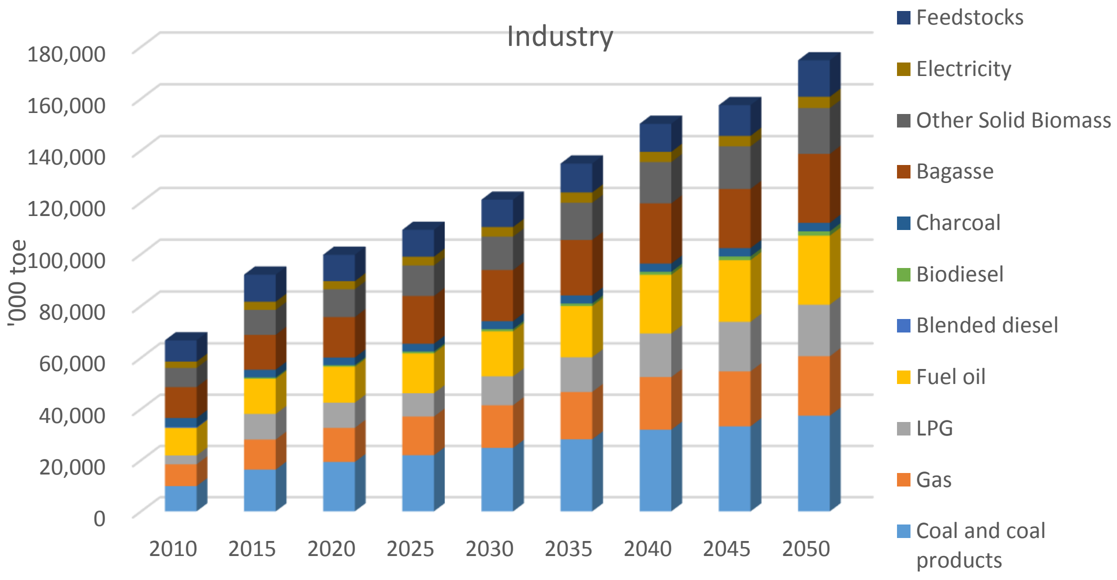

Figure A- 7 – Industry Consumption of scenario BASE_SOC – ktoe

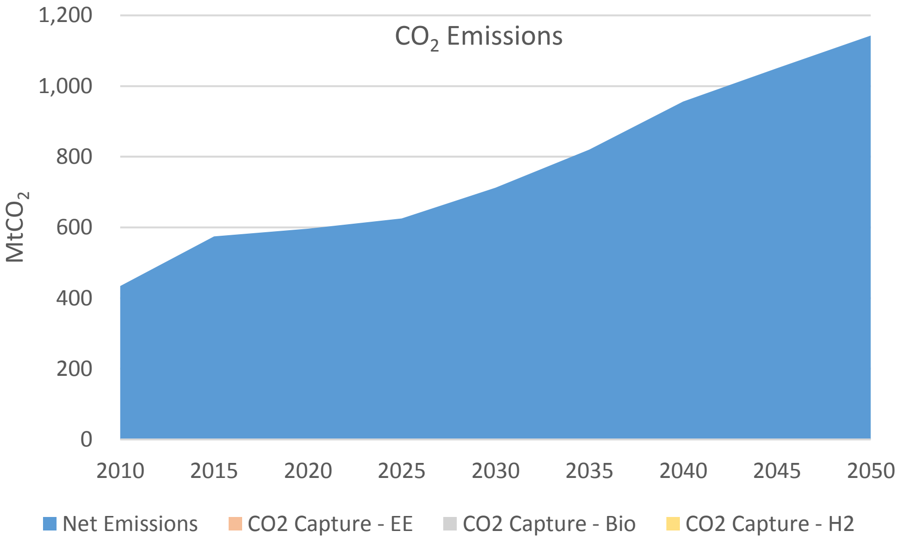

Figure A- 8 – CO_2 Emissions of scenario BASE_SOC – $MtCO_2$

Scenario LC_SOC_PF

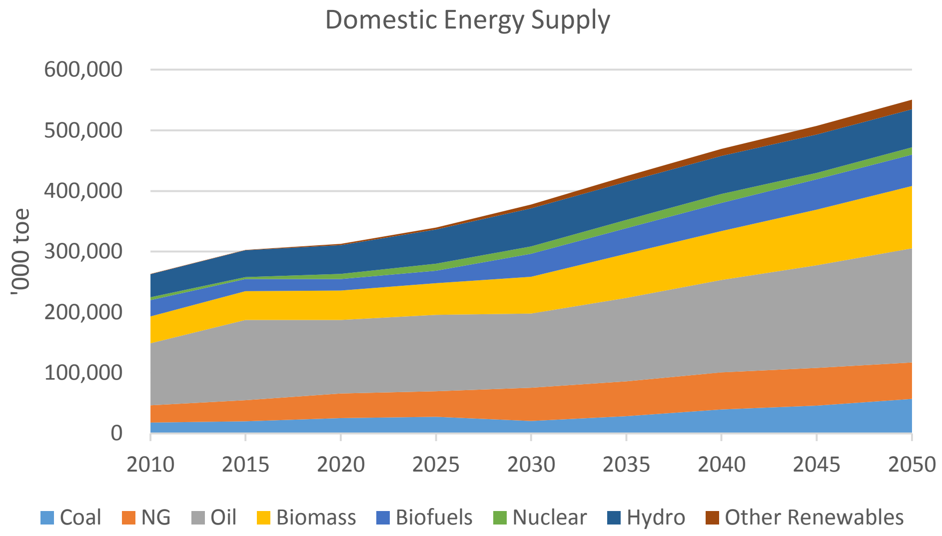

Figure A- 9 – Domestic Primary Energy Supply of scenario LC_SOC_PF – ktoe

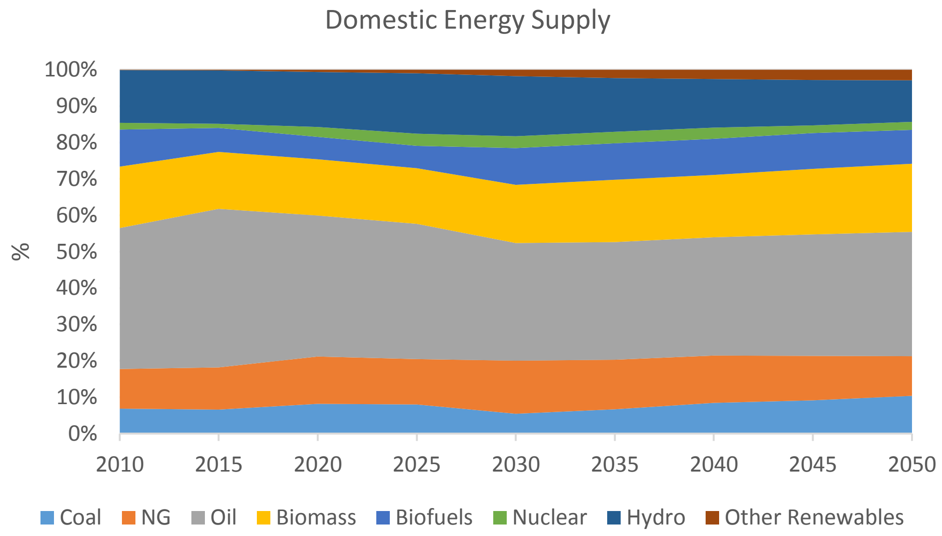

Figure A- 10 – Domestic Primary Energy Supply of scenario LC_SOC_PF - %

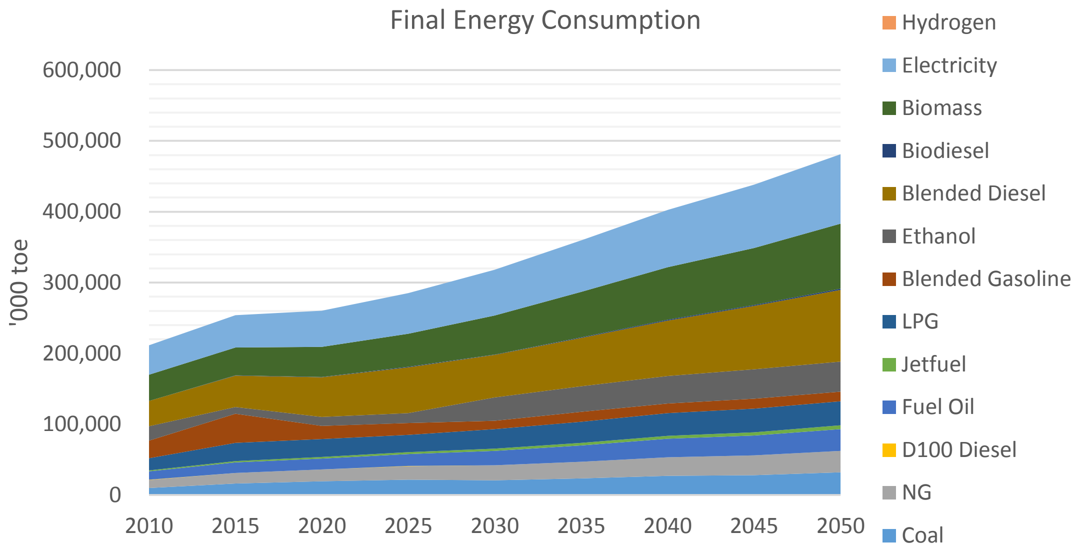

Figure A- 11 – Final Energy Consumption of scenario LC_SOC_PF – ktoe

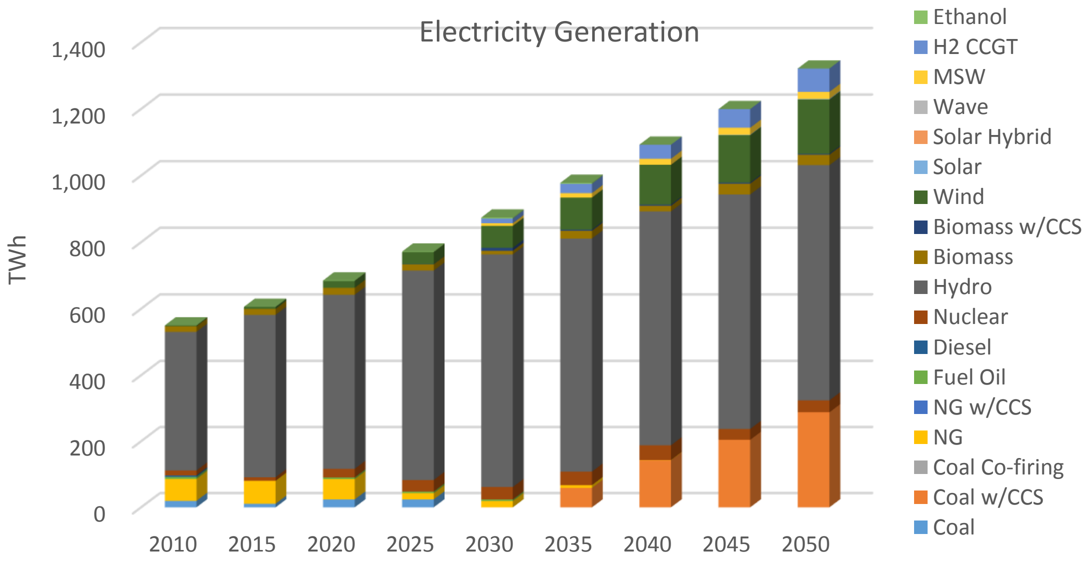

Figure A- 12 – Electricity Generation of scenario LC_SOC_PF – TWh

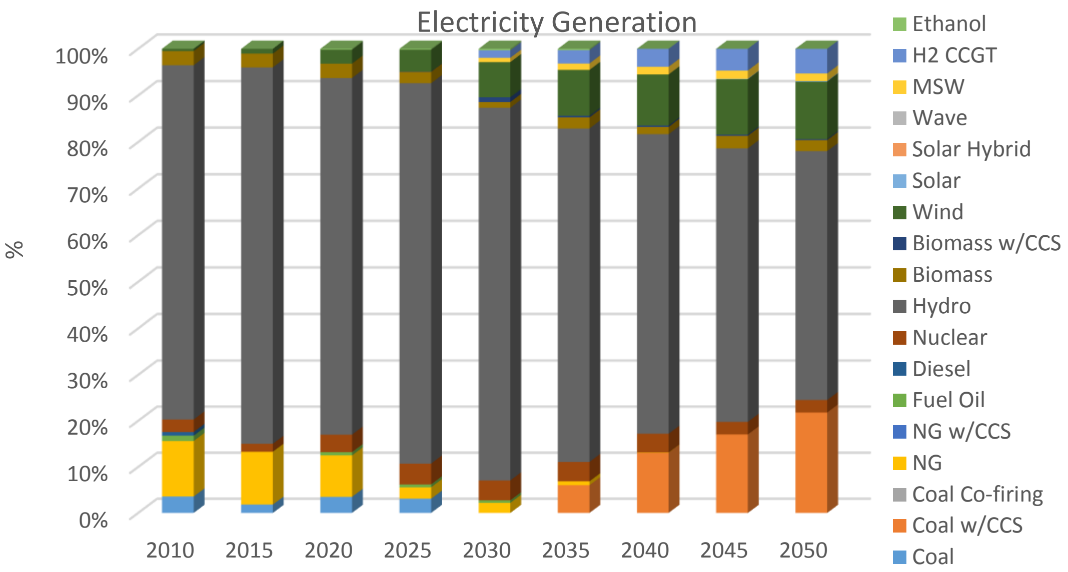

Figure A- 13 – Electricity Generation of scenario LC_SOC_PF – %

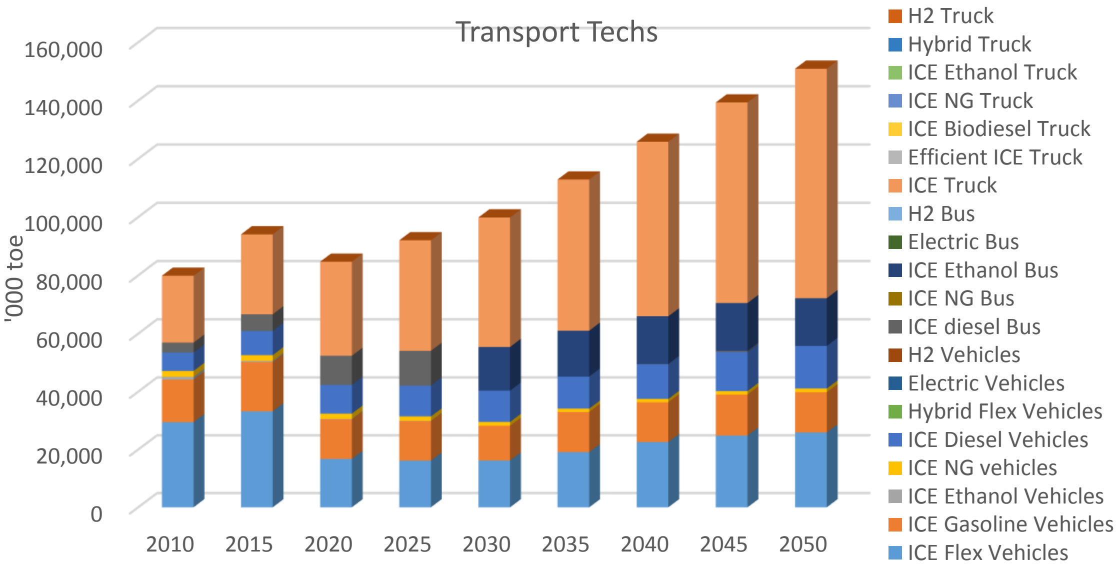

Figure A- 14 – Transport Sector Consumption of scenario LC_SOC_PF – ktoe

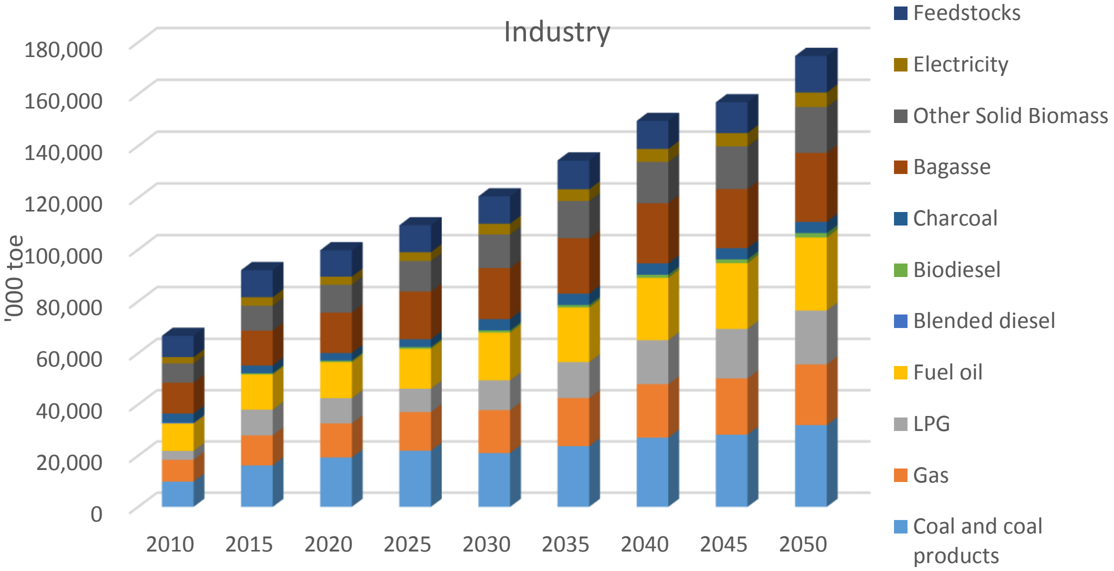

Figure A- 15 – Industry Consumption of scenario LC_SOC_PF – ktoe

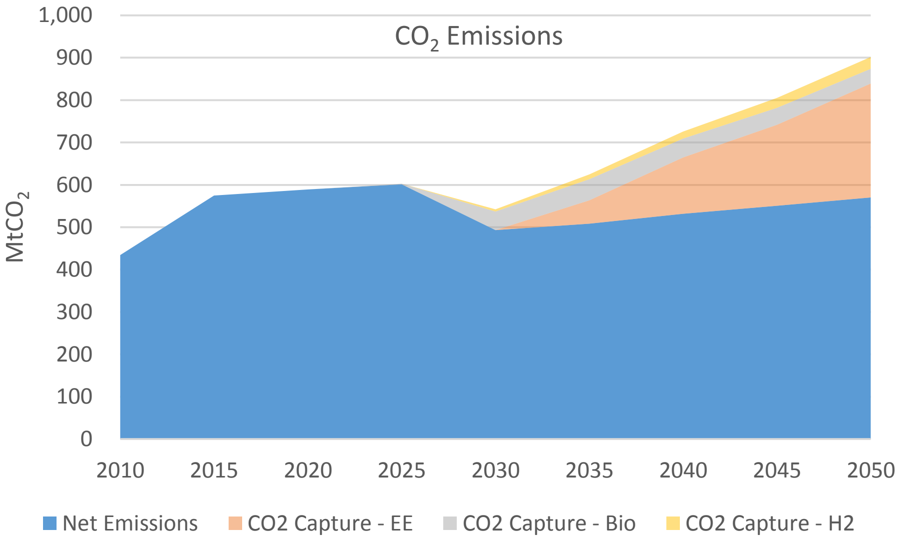

Figure A- 16 – CO_2 Emissions of scenario LC_SOC_PF – $MtCO_2$

Scenario LC_SOC_M

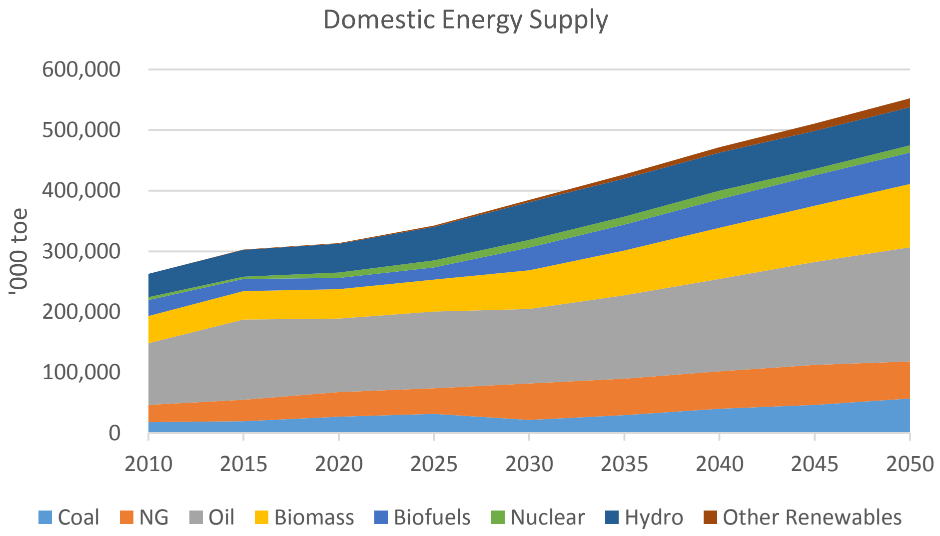

Figure A- 17 – Domestic Primary Energy Supply of scenario LC_SOC_M – ktoe

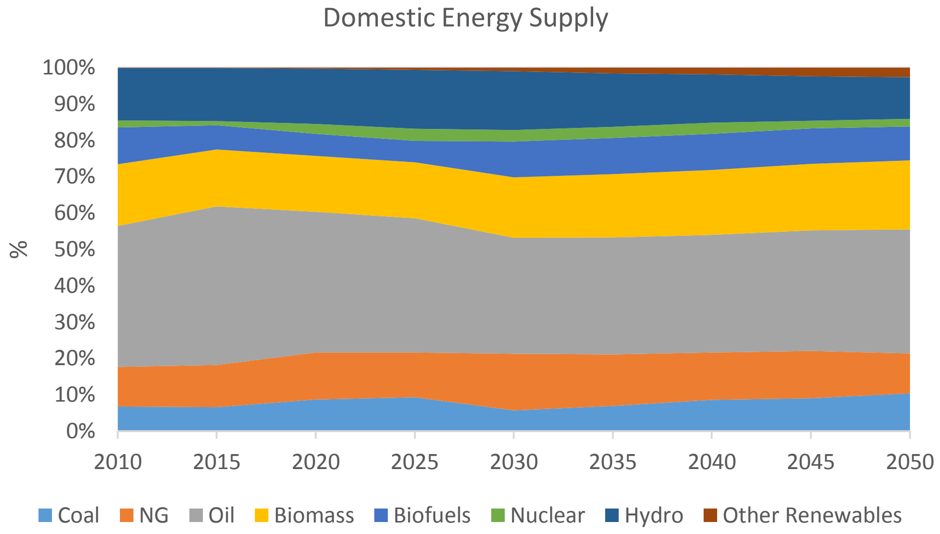

Figure A- 18 – Domestic Primary Energy Supply of scenario LC_SOC_M - %

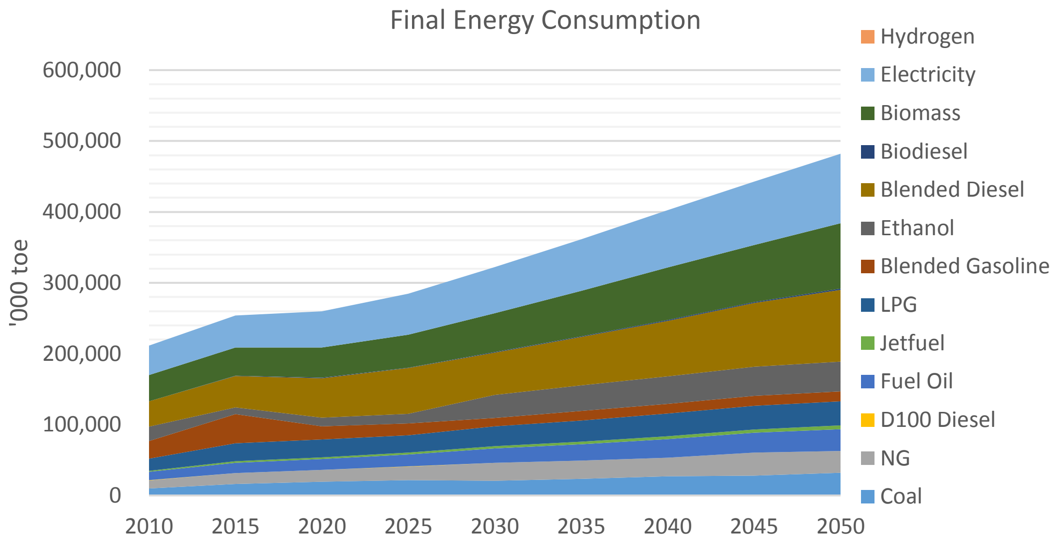

Figure A- 19 – Final Energy Consumption of scenario LC_SOC_M – ktoe

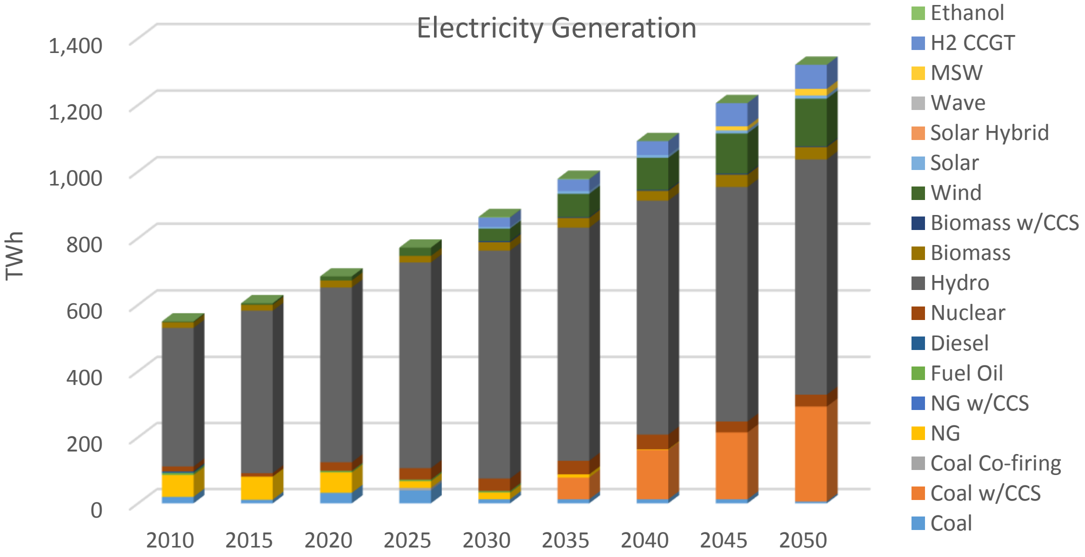

Figure A- 20 – Electricity Generation of scenario LC_SOC_M – TWh

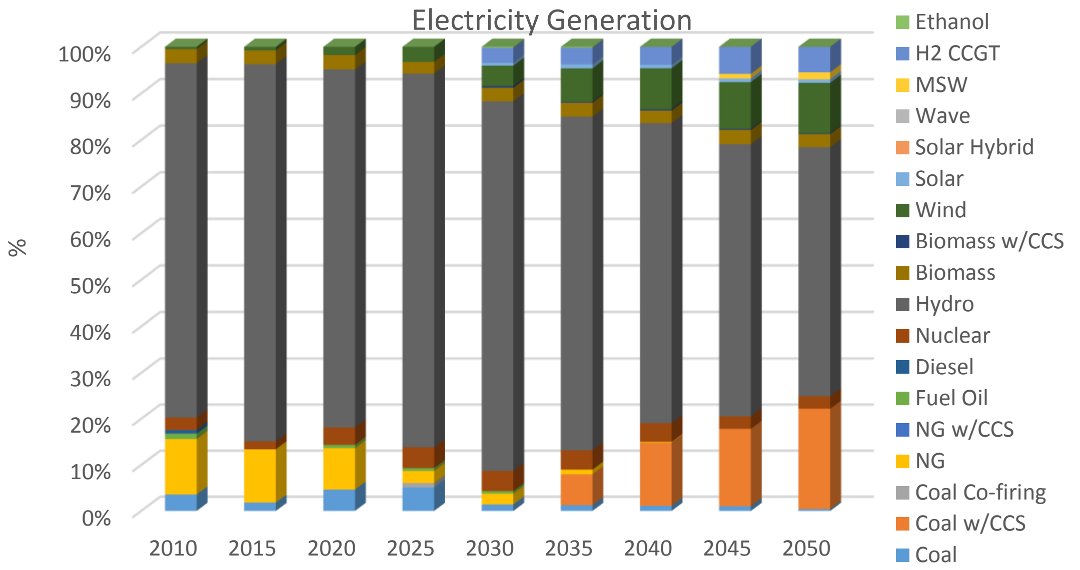

Figure A- 21 – Electricity Generation of scenario LC_SOC_M – %

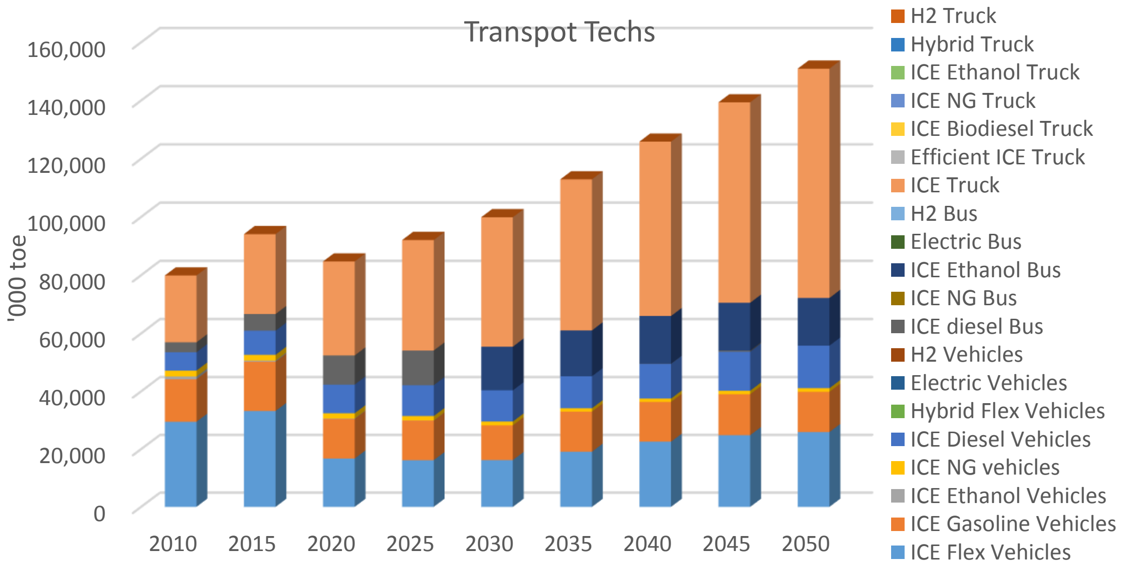

Figure A- 22 – Transport Sector Consumption of scenario LC_SOC_M – ktoe

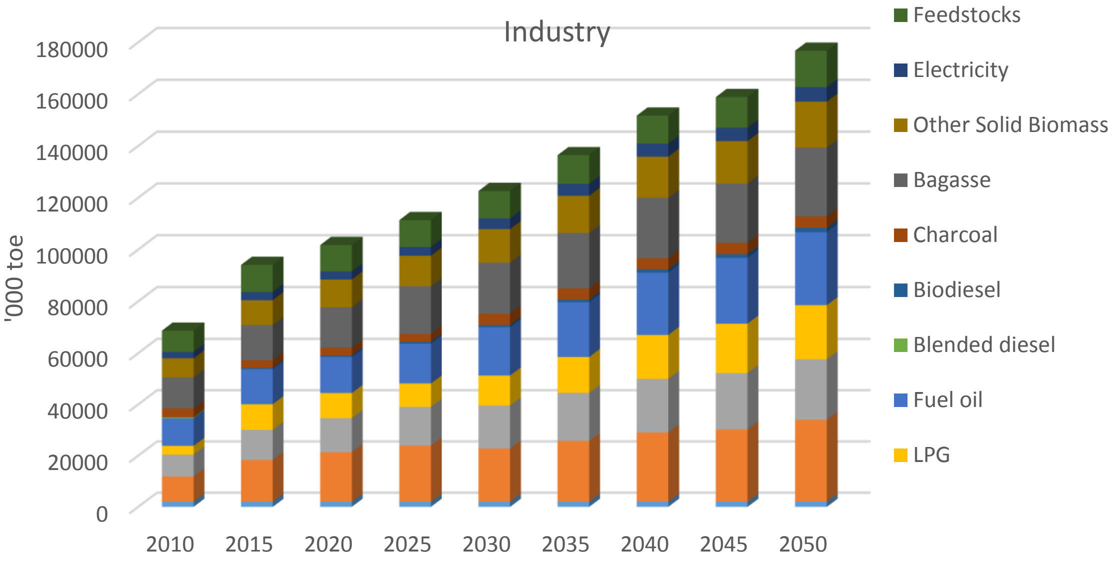

Figure A- 23 – Industry Consumption of scenario LC_SOC_M – ktoe

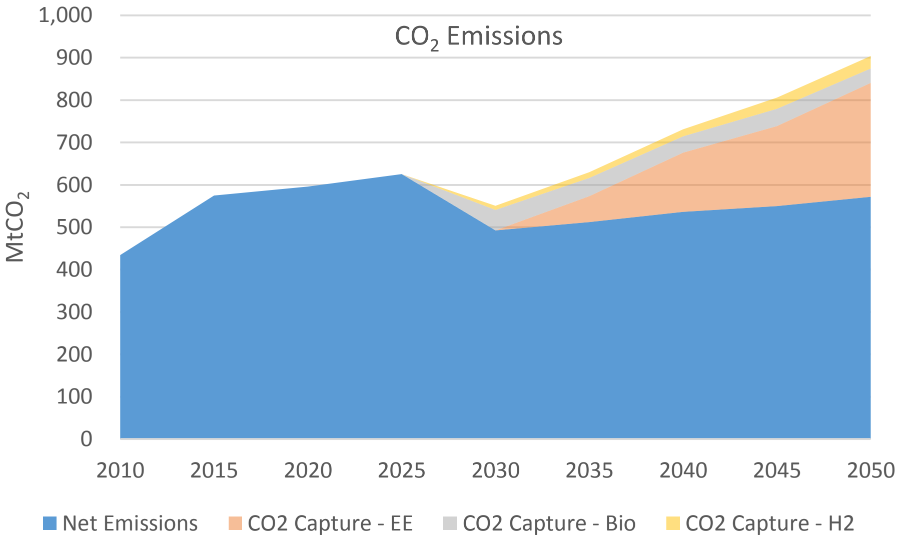

Figure A- 24 – CO_2 Emissions of scenario LC_SOC_M – $MtCO_2$

Scenario LC_SOC_PFD

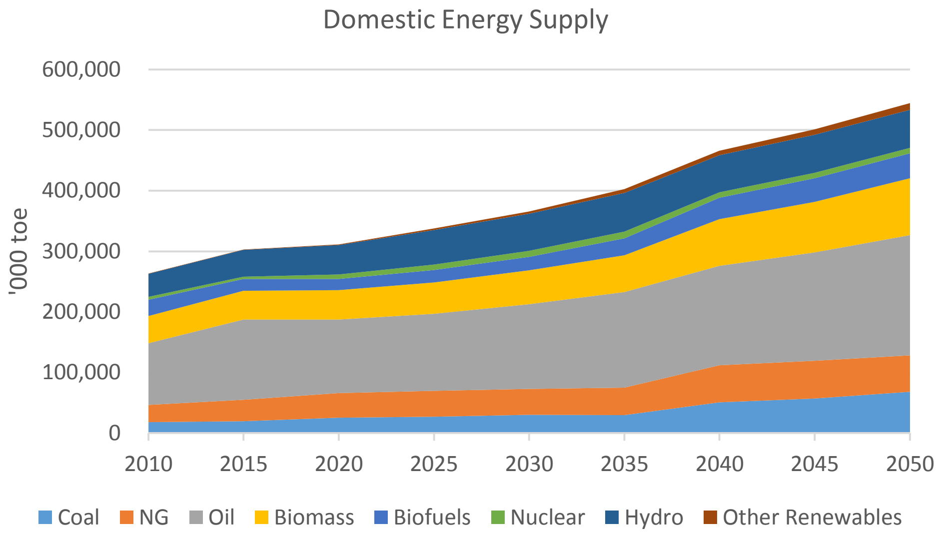

Figure A- 25 – Domestic Primary Energy Supply of scenario LC_SOC_PFD – ktoe

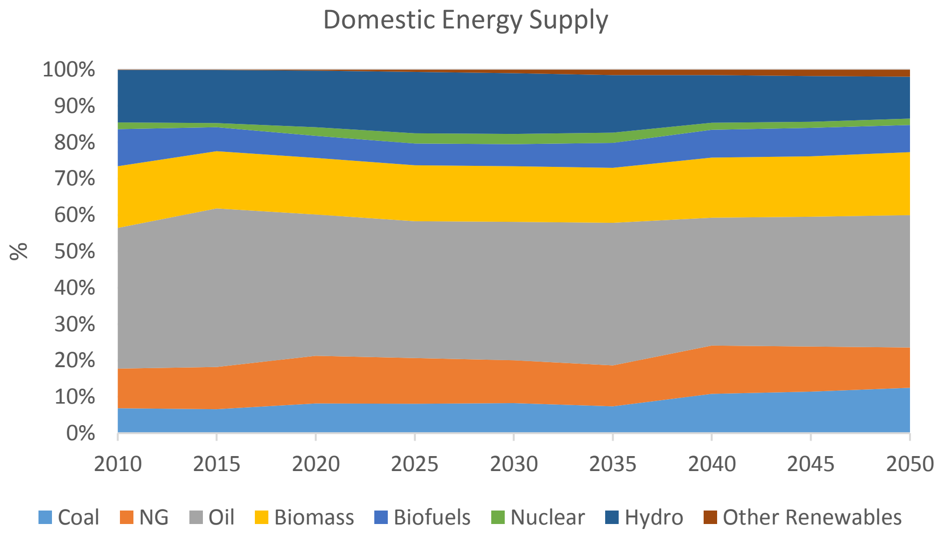

Figure A- 26 – Domestic Primary Energy Supply of scenario LC_SOC_PFD - %

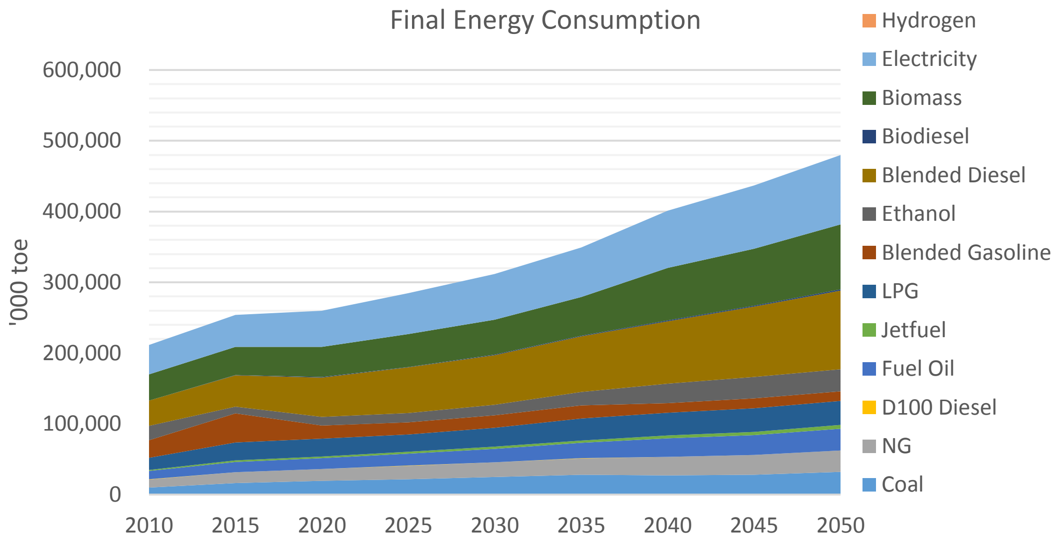

Figure A- 27 – Final Energy Consumption of scenario LC_SOC_PFD – ktoe

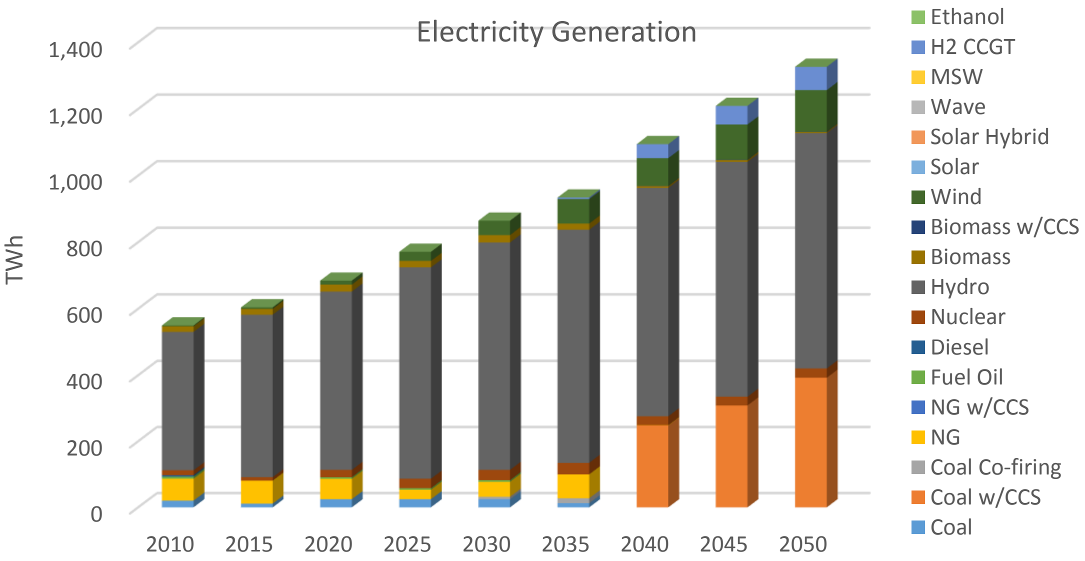

Figure A- 28 – Electricity Generation of scenario LC_SOC_PFD – TWh

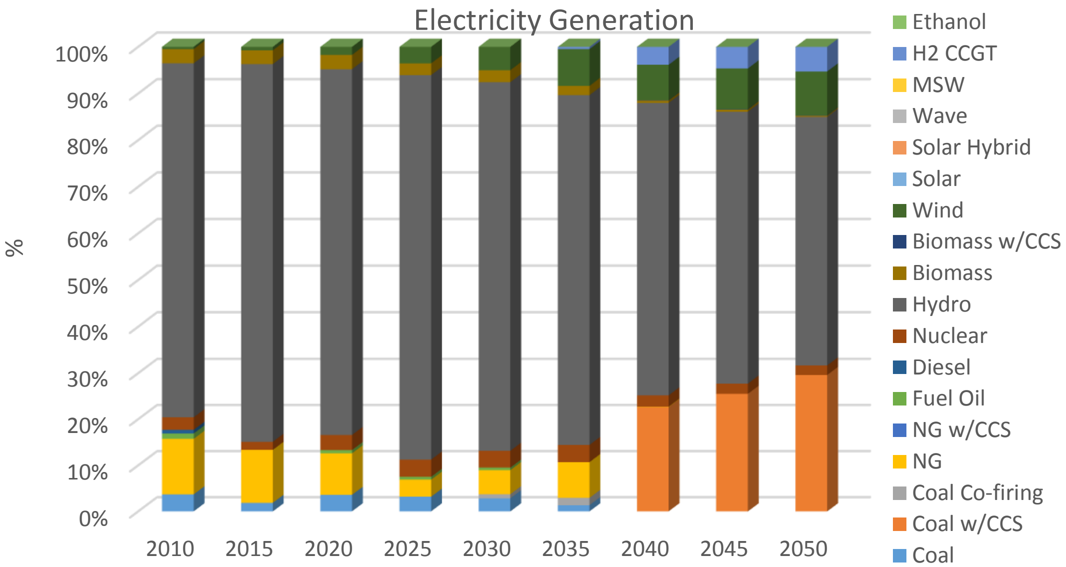

Figure A- 29 – Electricity Generation of scenario LC_SOC_PFD – %

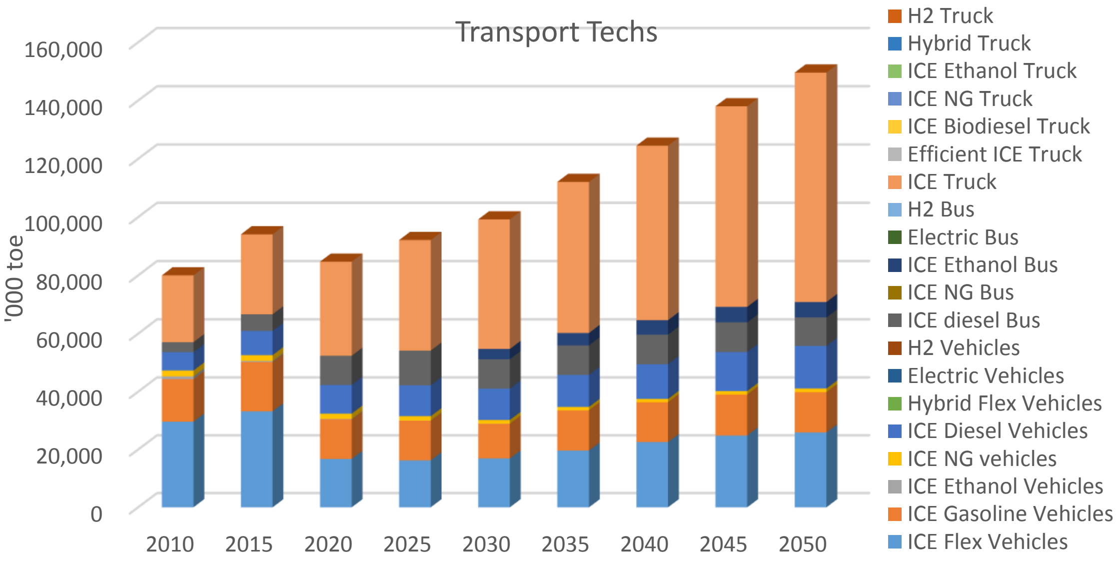

Figure A- 30 – Transport Sector Consumption of scenario LC_SOC_PFD – ktoe

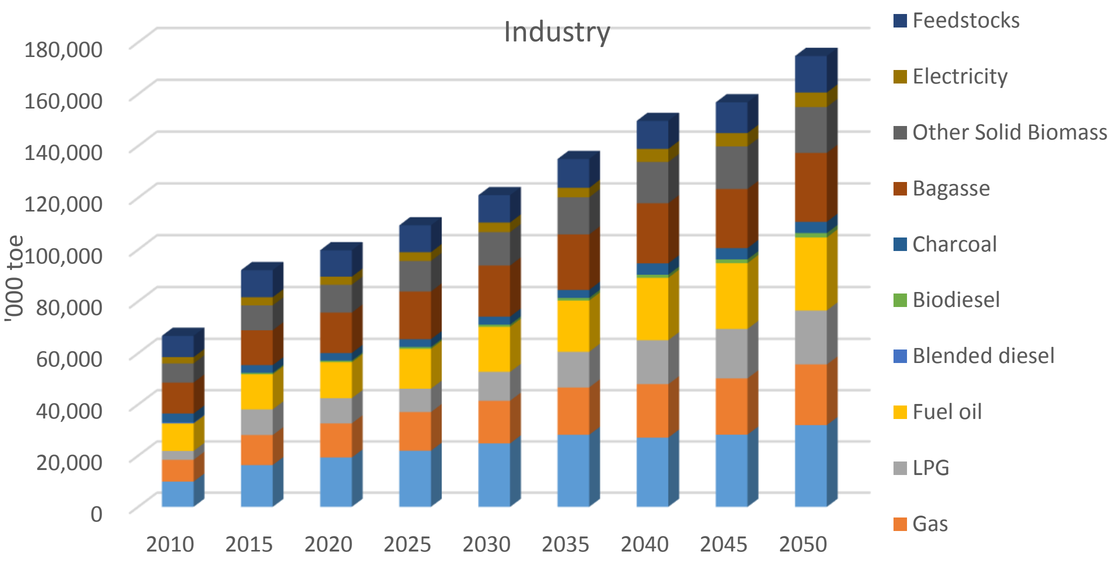

Figure A- 31 – Industry Consumption of scenario LC_SOC_PFD – ktoe

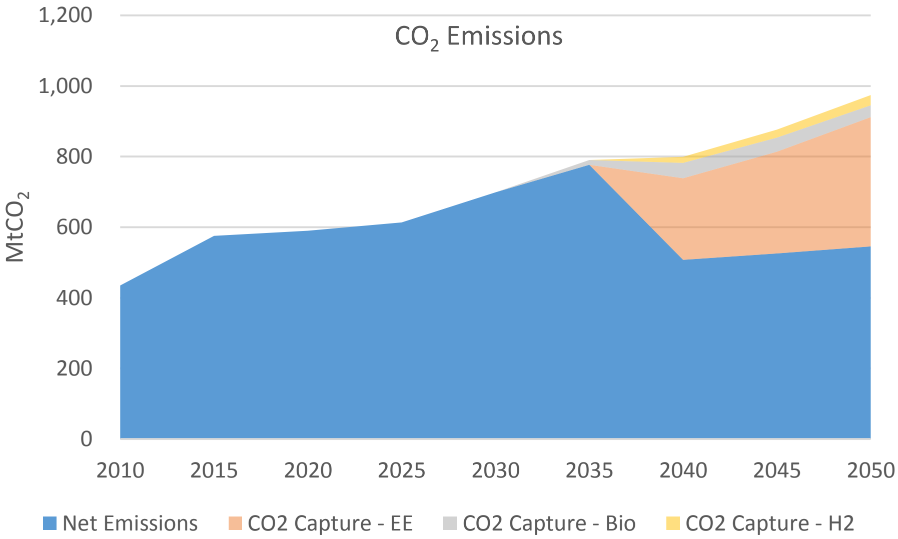

Figure A- 32 – CO_2 Emissions of scenario LC_SOC_PFD – $MtCO_2$

Scenario LC_SOC_MD

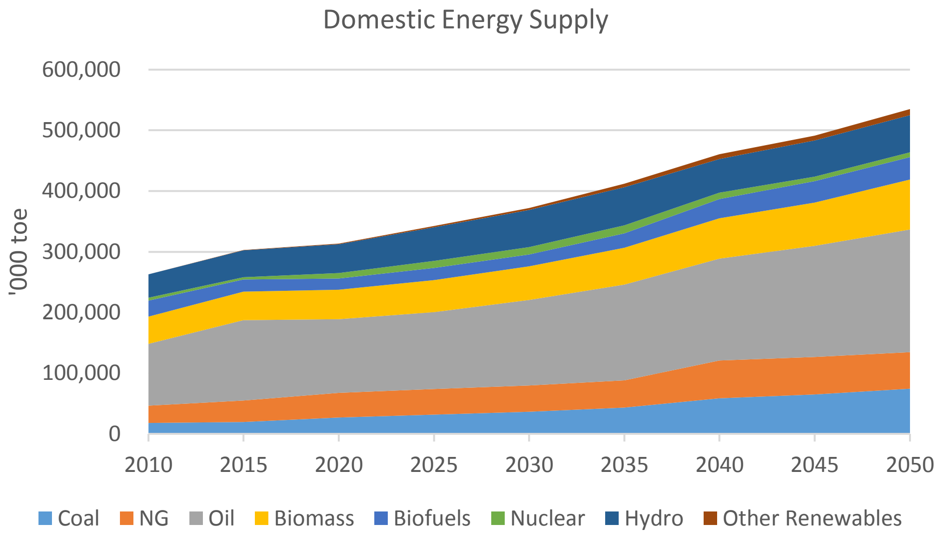

Figure A- 33 – Domestic Primary Energy Supply of scenario LC_SOC_MD – ktoe

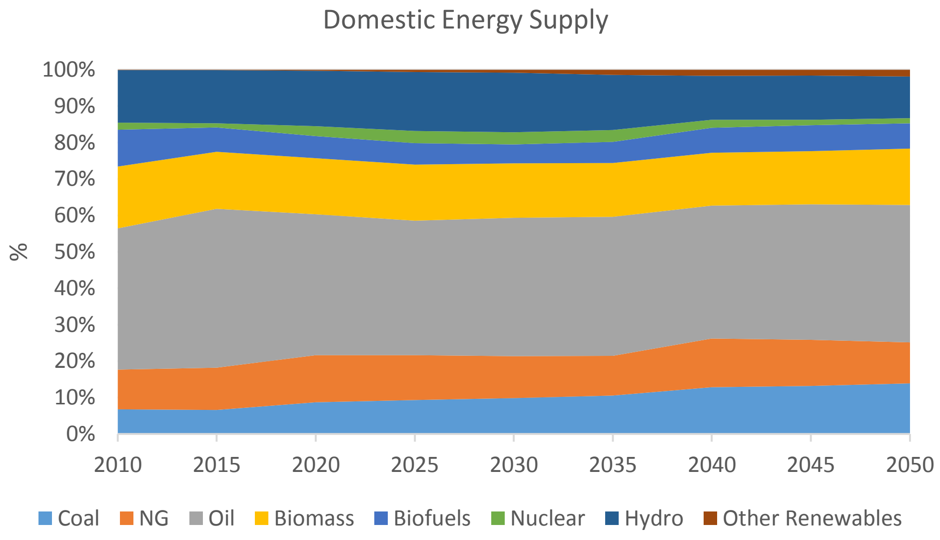

Figure A- 34 – Domestic Primary Energy Supply of scenario LC_SOC_MD - %

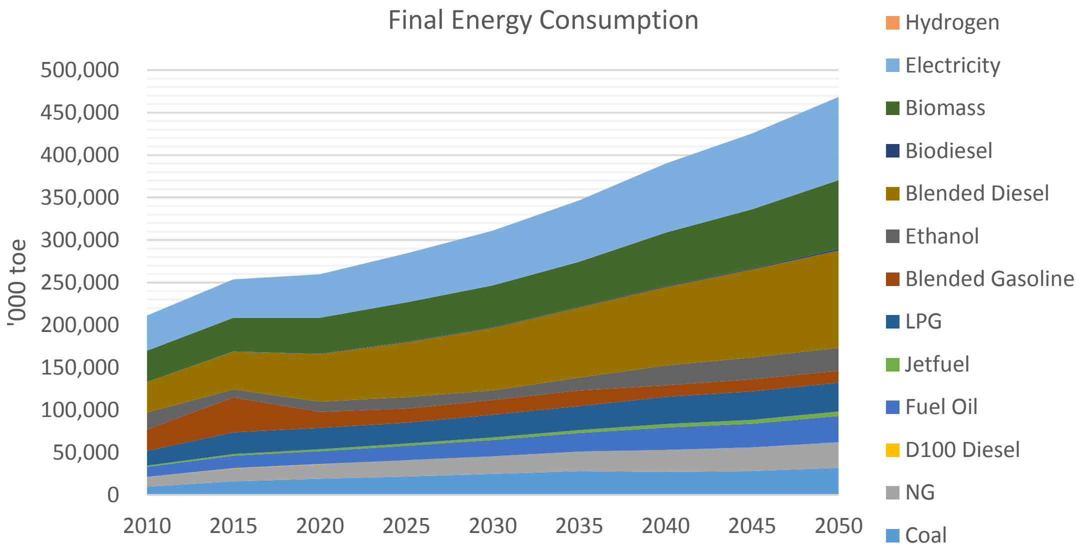

Figure A- 35 – Final Energy Consumption of scenario LC_SOC_MD – ktoe

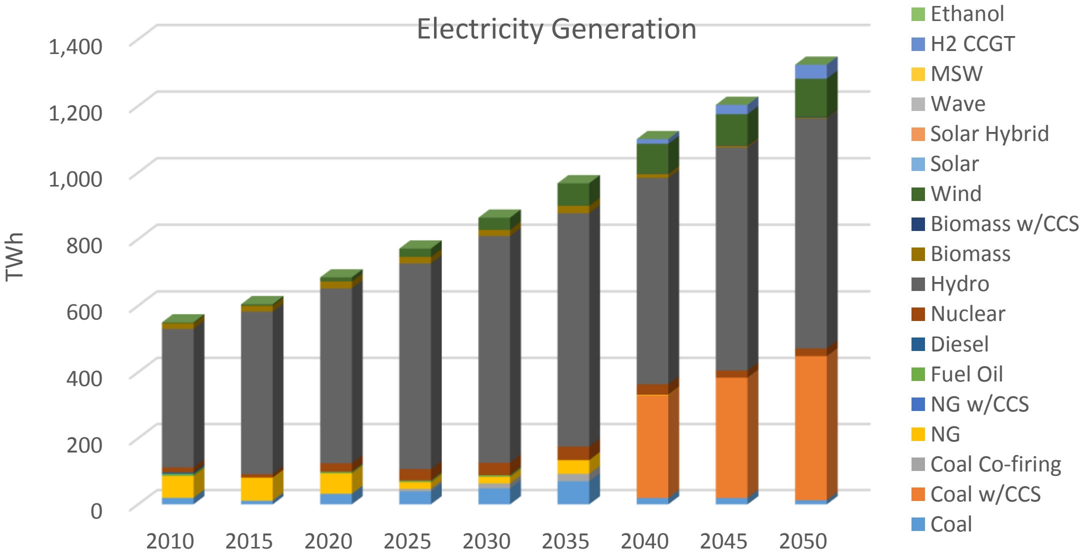

Figure A- 36 – Electricity Generation of scenario LC_SOC_MD – TWh

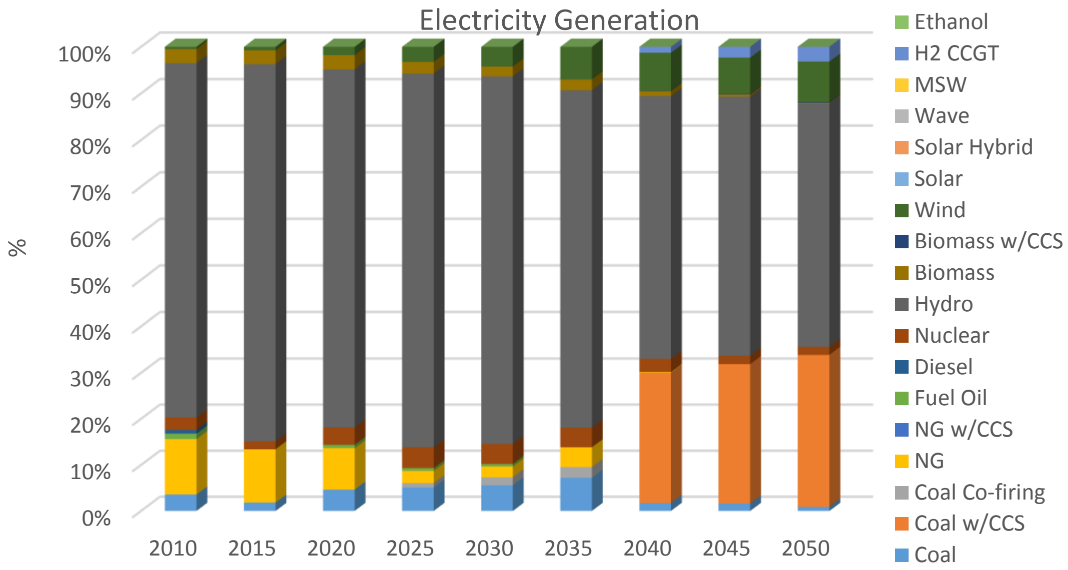

Figure A- 37 – Electricity Generation of scenario LC_SOC_MD – %

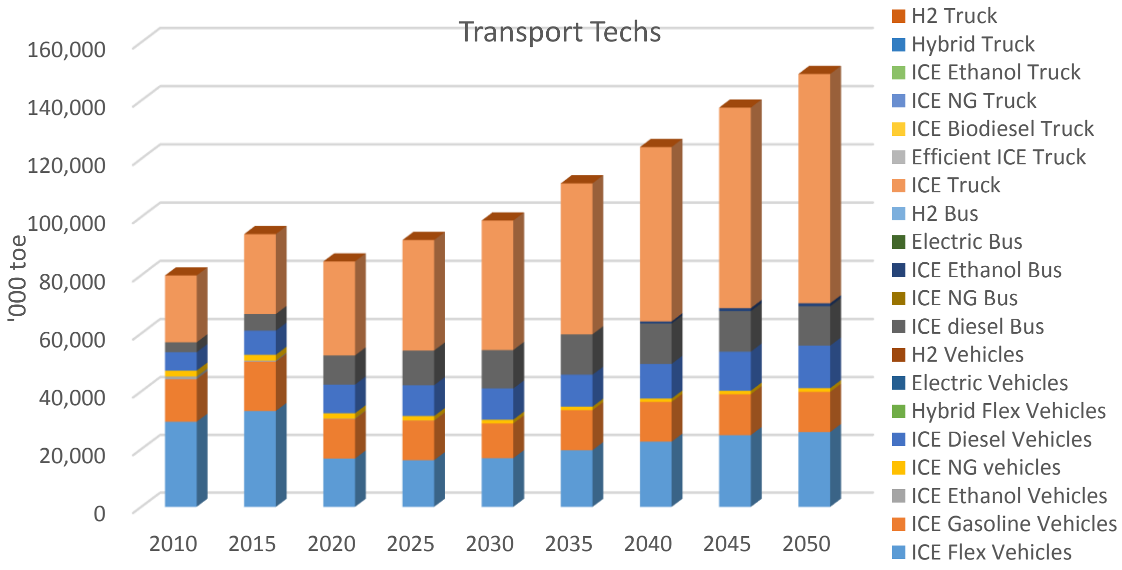

Figure A- 38 – Transport Sector Consumption of scenario LC_SOC_MD – ktoe

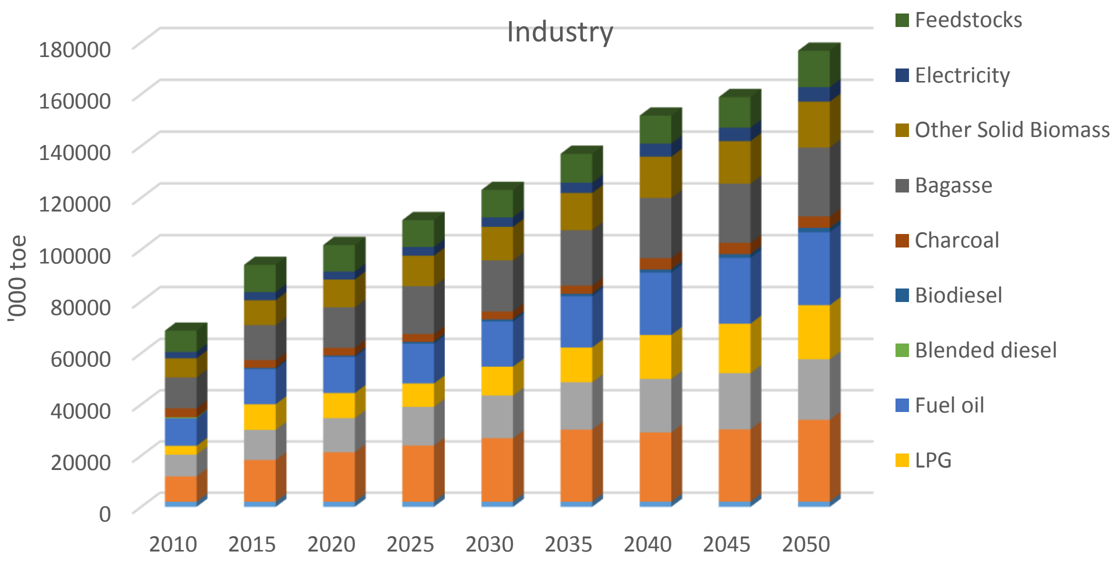

Figure A- 39 – Industry Consumption of scenario LC_SOC_MD – ktoe

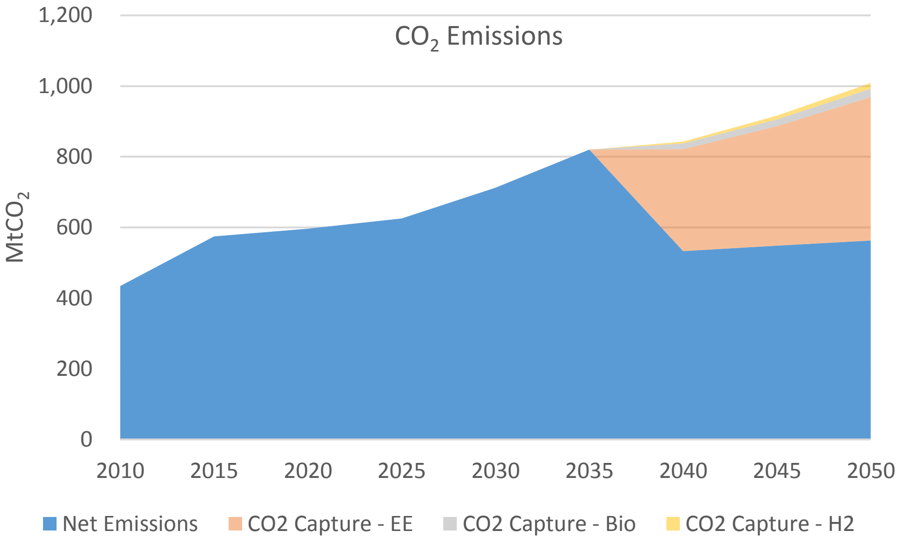

Figure A- 40 – CO_2 Emissions of scenario LC_SOC_MD – $MtCO_2$

Scenario BASE_MKTS

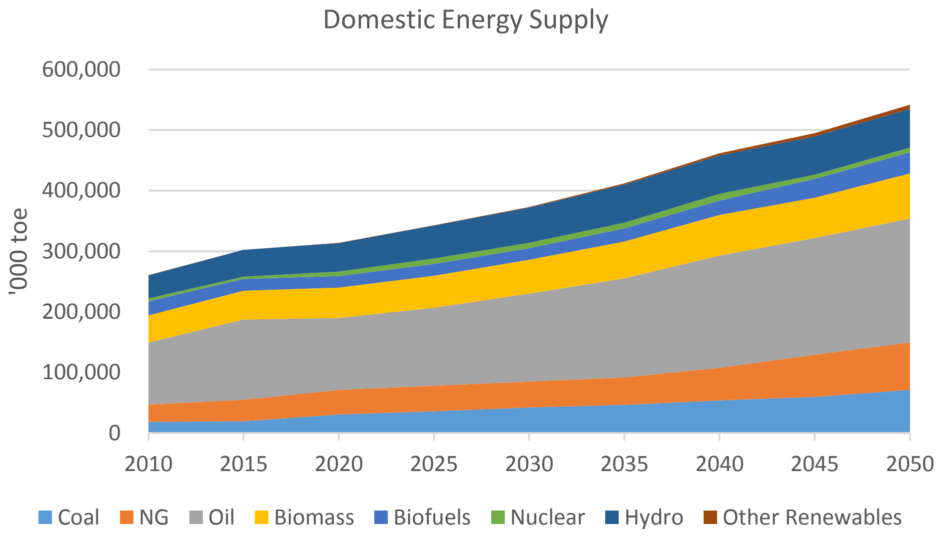

Figure A- 41 – Domestic Primary Energy Supply of scenario BASE_MKTS – ktoe

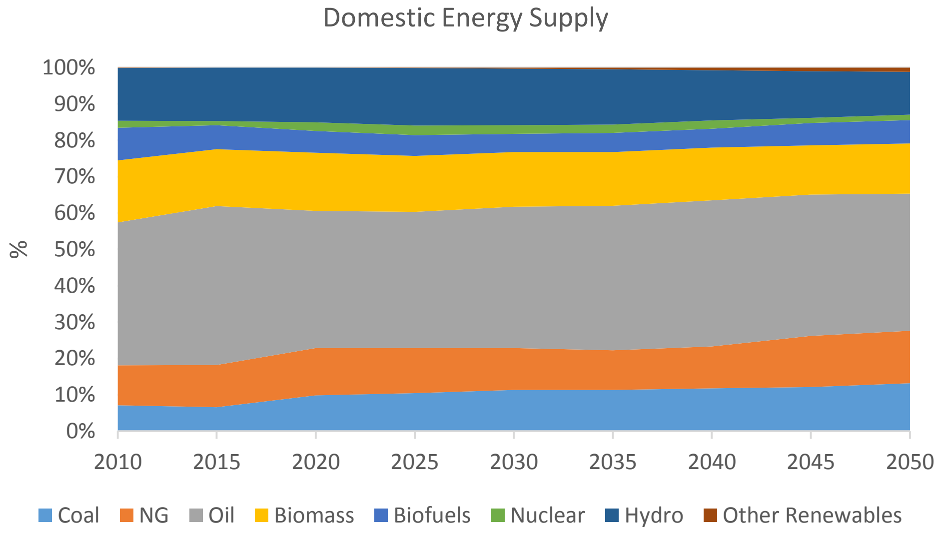

Figure A- 42 – Domestic Primary Energy Supply of scenario BASE_MKTS - %

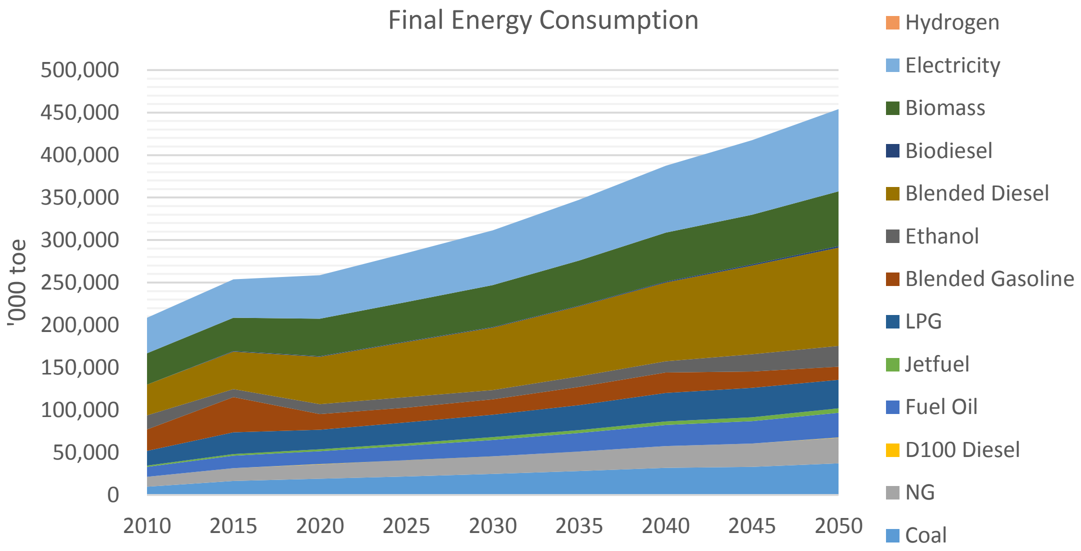

Figure A- 43 – Final Energy Consumption of scenario BASE_MKTS – ktoe

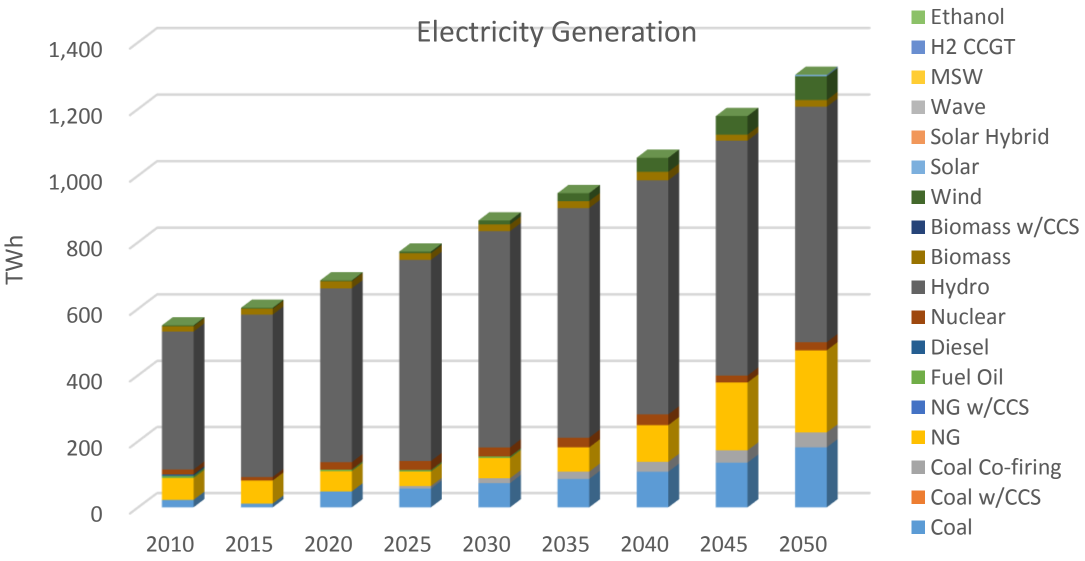

Figure A- 44 – Electricity Generation of scenario BASE_MKTS – TWh

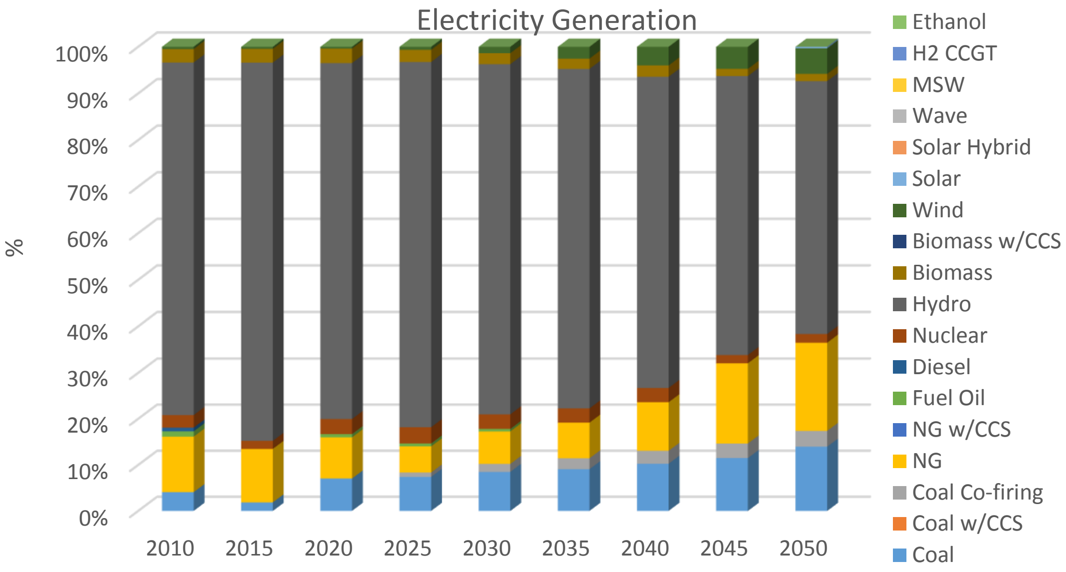

Figure A- 45 – Electricity Generation of scenario BASE_MKTS – %

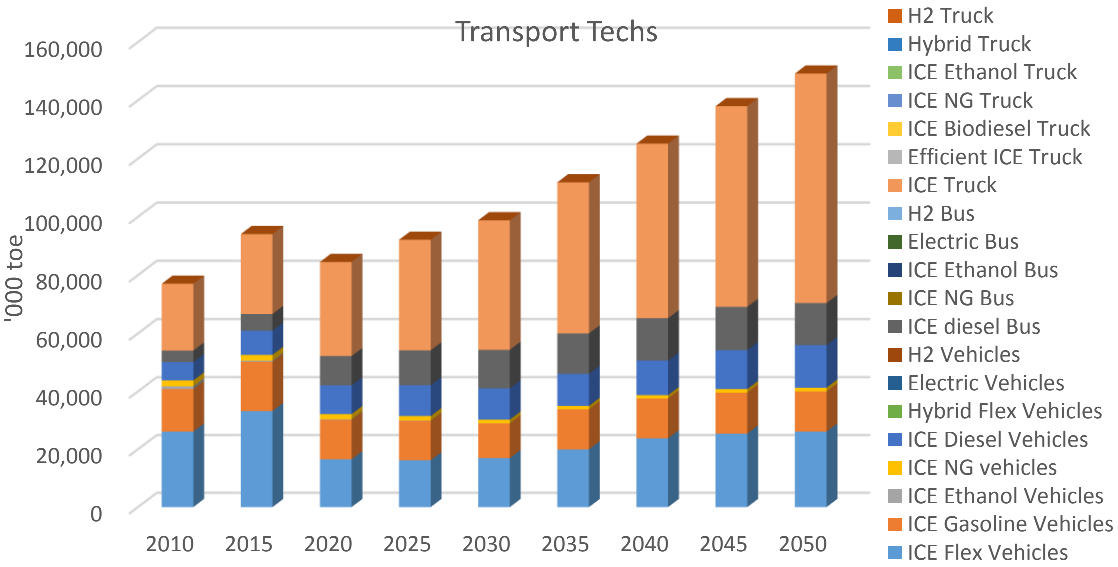

Figure A- 46 – Transport Sector Consumption of scenario BASE_MKTS – ktoe

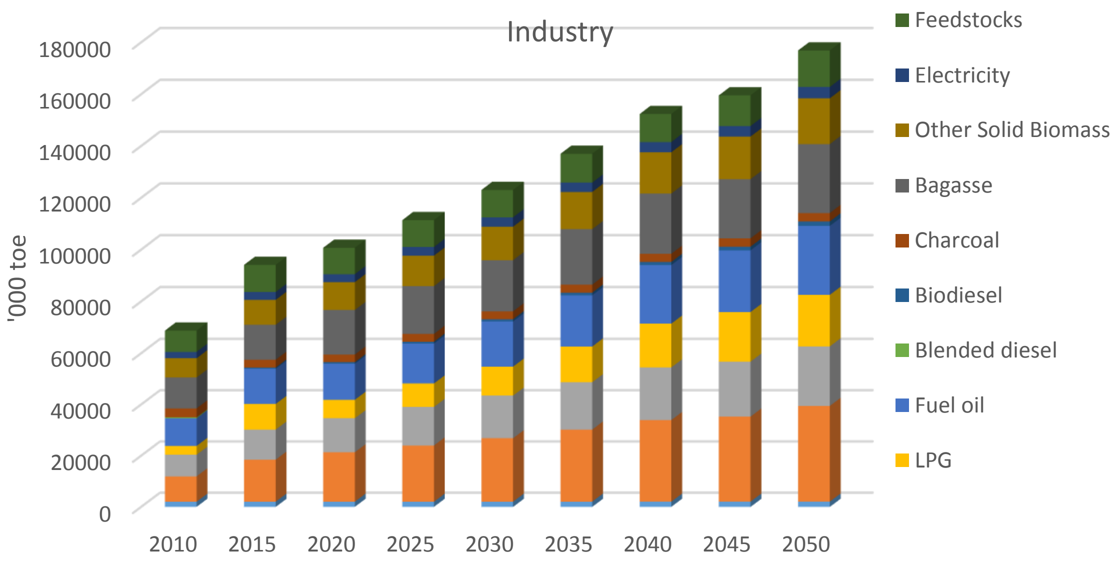

Figure A- 47 – Industry Consumption of scenario BASE_MKTS – ktoe

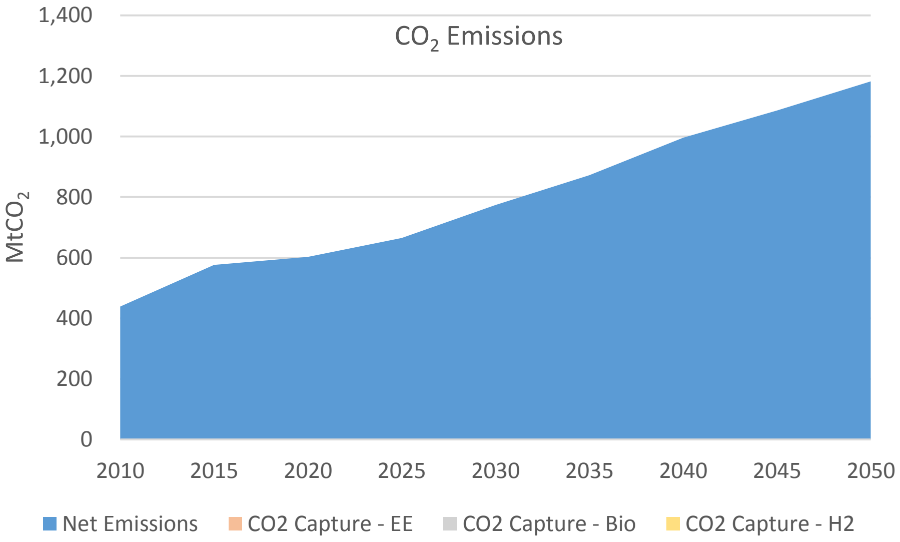

Figure A- 48 – CO_2 Emissions of scenario BASE_MKTS – $MtCO_2$

Scenario BASE_MKT

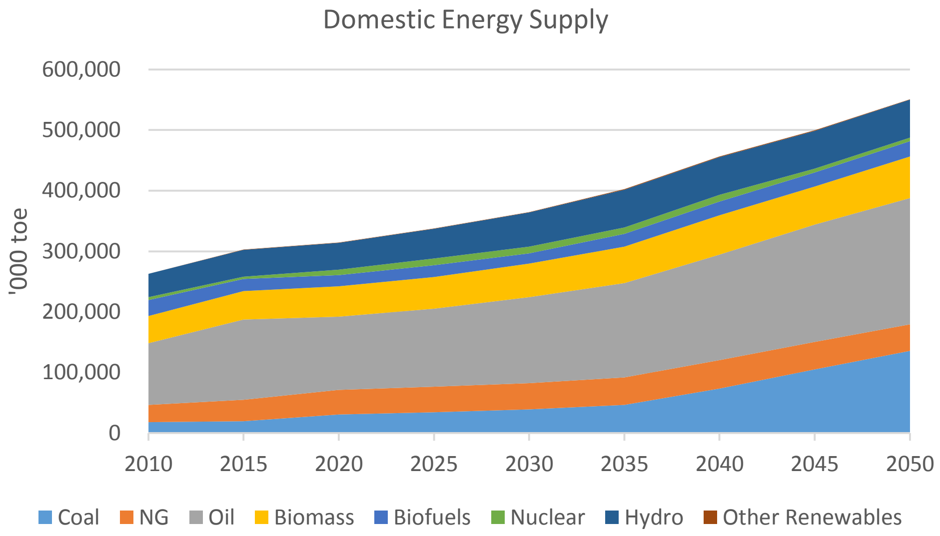

Figure A- 49 – Domestic Primary Energy Supply of scenario BASE_MKT – ktoe

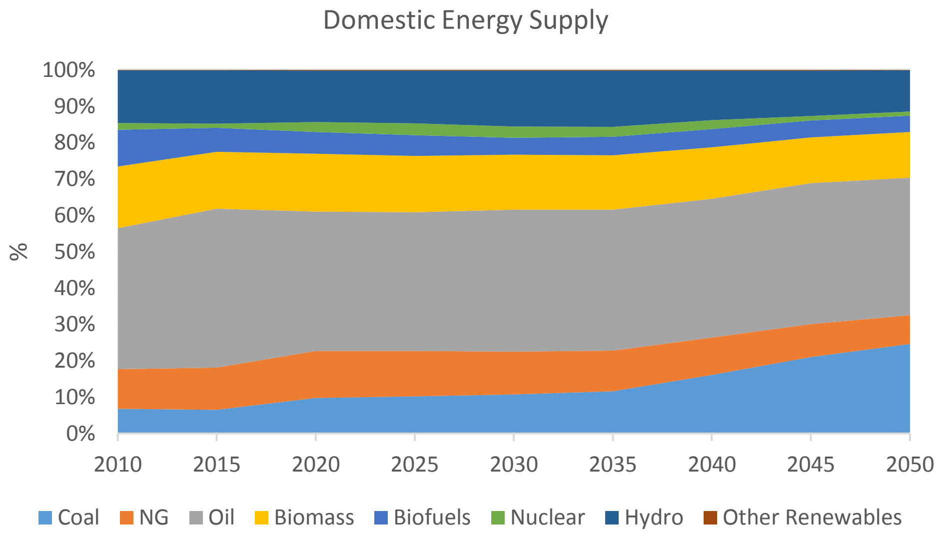

Figure A- 50 – Domestic Primary Energy Supply of scenario BASE_MKT - %

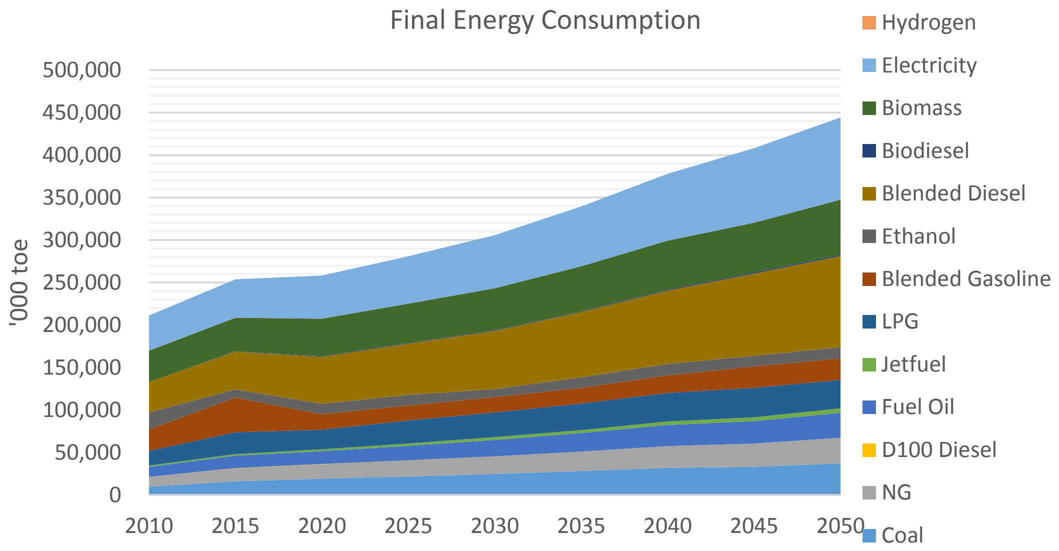

Figure A- 51 – Final Energy Consumption of scenario BASE_MKTS – ktoe

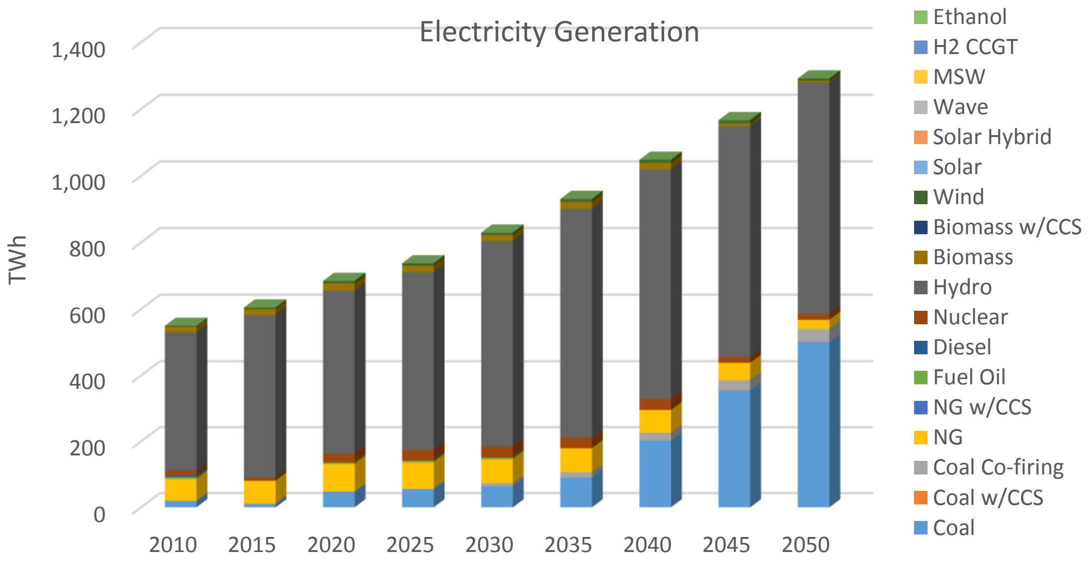

Figure A- 52 – Electricity Generation of scenario BASE_MKTS – TWh

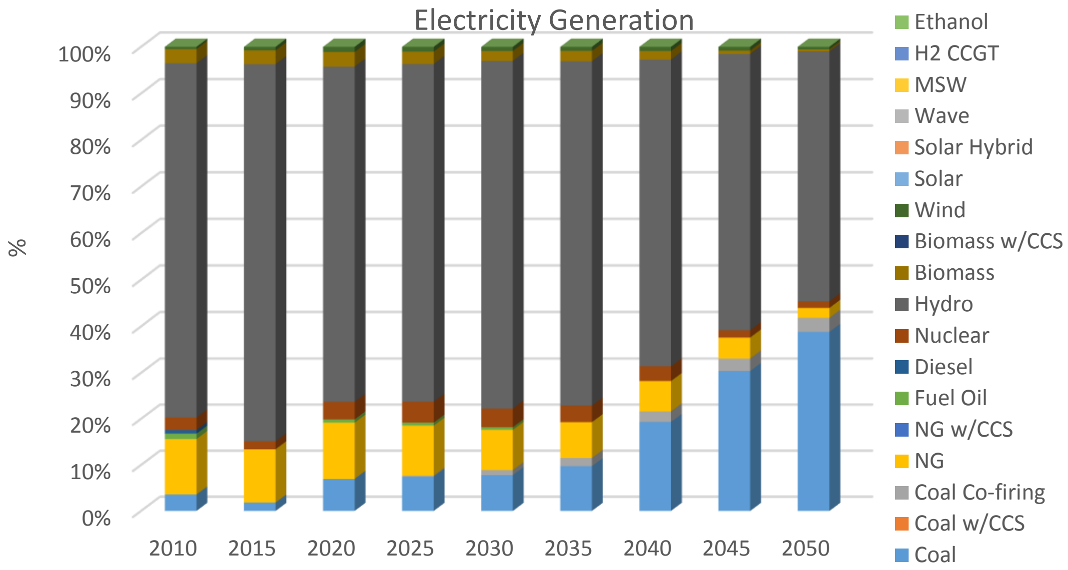

Figure A- 53 – Electricity Generation of scenario BASE_MKTS – %

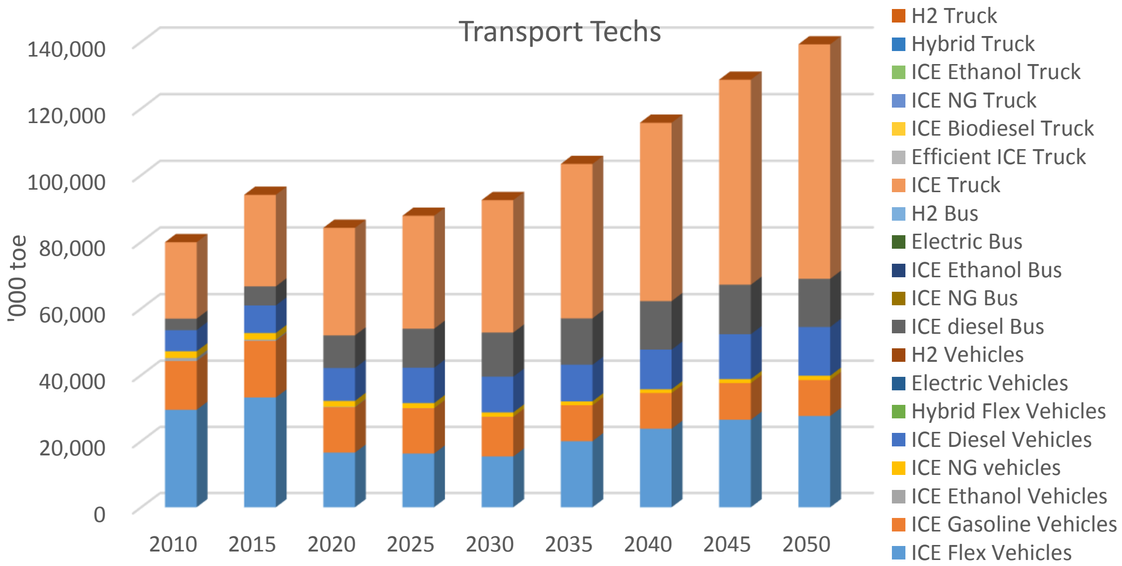

Figure A- 54 – Transport Sector Consumption of scenario BASE_MKTS – ktoe

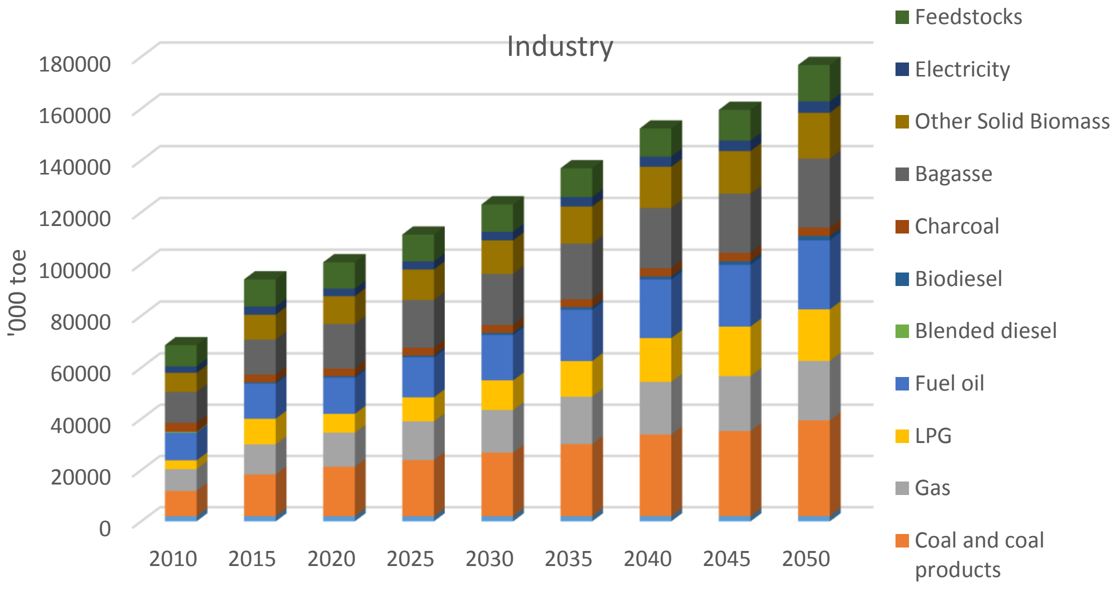

Figure A- 55 – Industry Consumption of scenario BASE_MKTS – ktoe

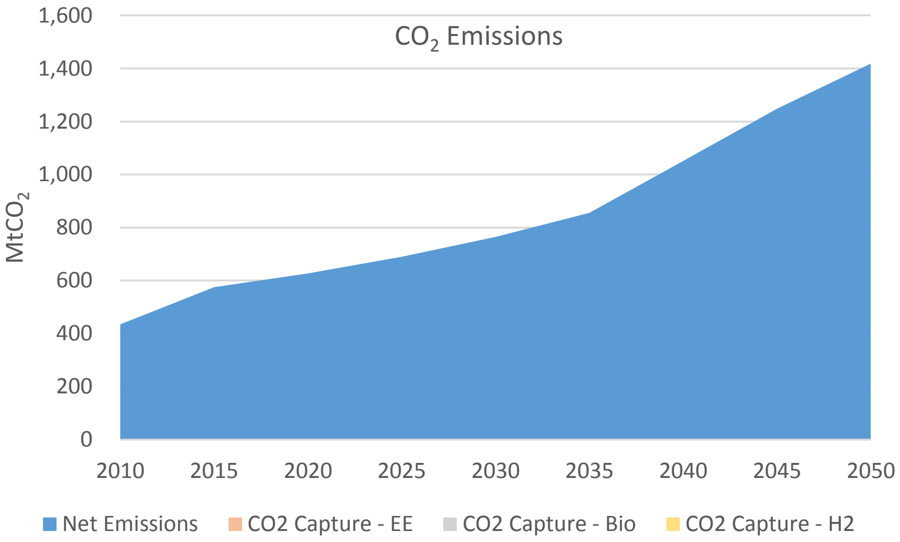

Figure A- 56 – CO_2 Emissions of scenario BASE_MKTS – $MtCO_2$

Scenario LC_MKTS_PF

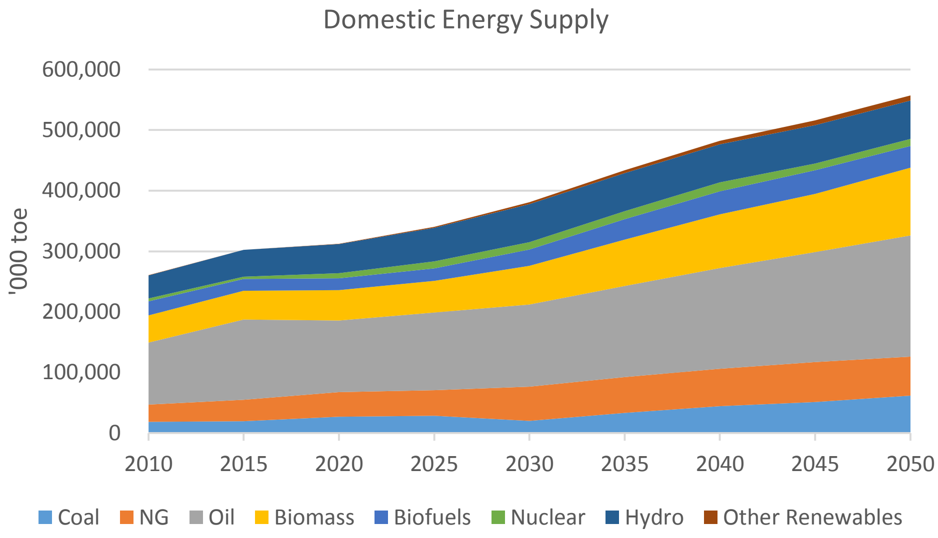

Figure A- 57 – Domestic Primary Energy Supply of scenario LC_MKTS_PF – ktoe

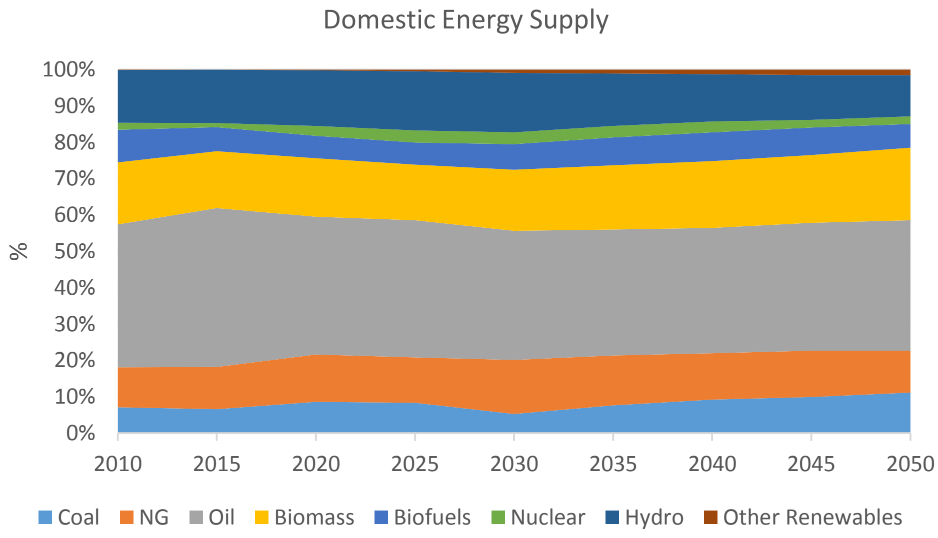

Figure A- 58 – Domestic Primary Energy Supply of scenario LC_MKTS_PF - %

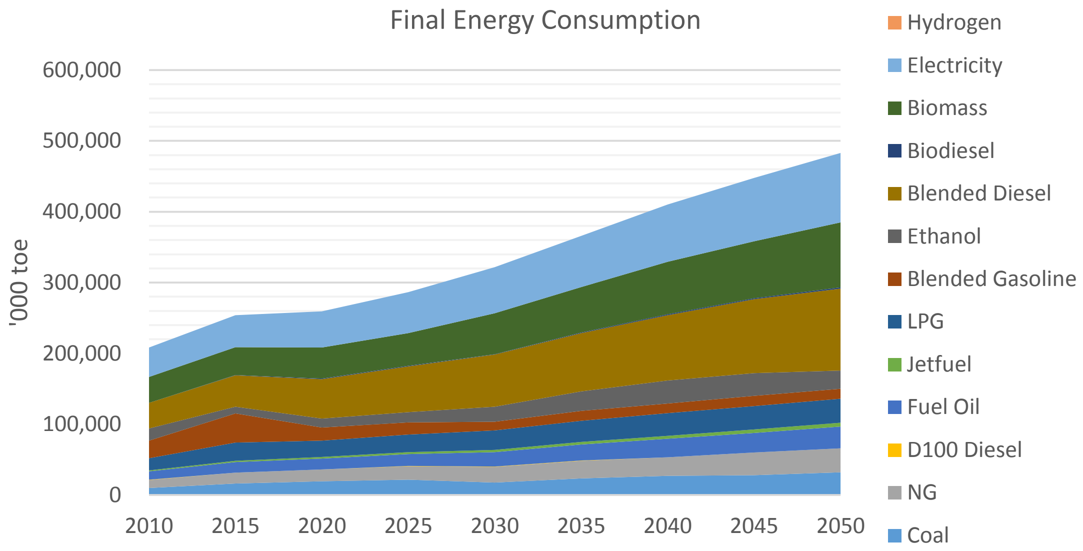

Figure A- 59 – Final Energy Consumption of scenario LC_MKTS_PF – ktoe

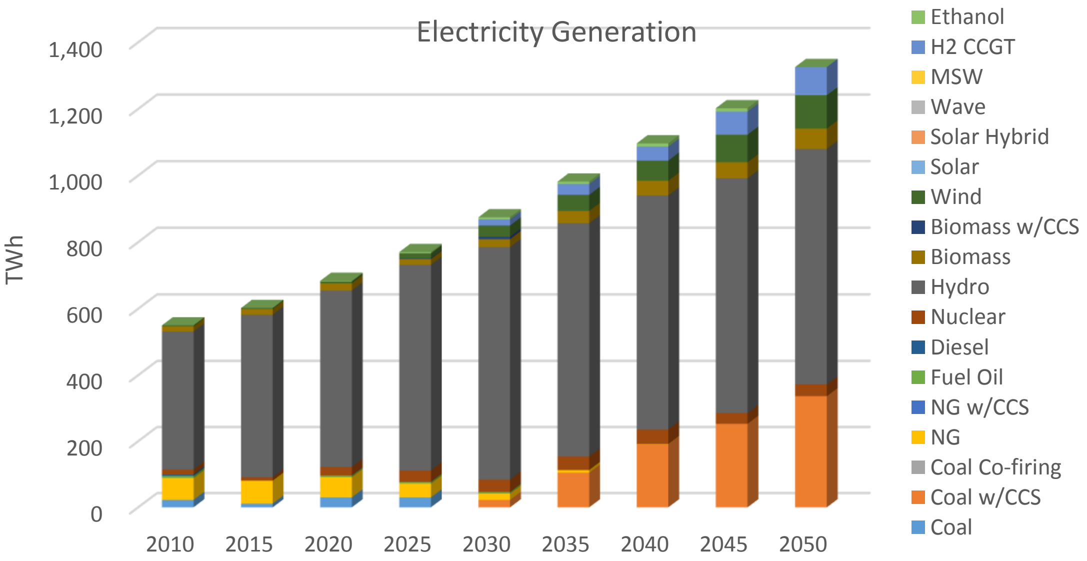

Figure A- 60 – Electricity Generation of scenario LC_MKTS_PF – TWh

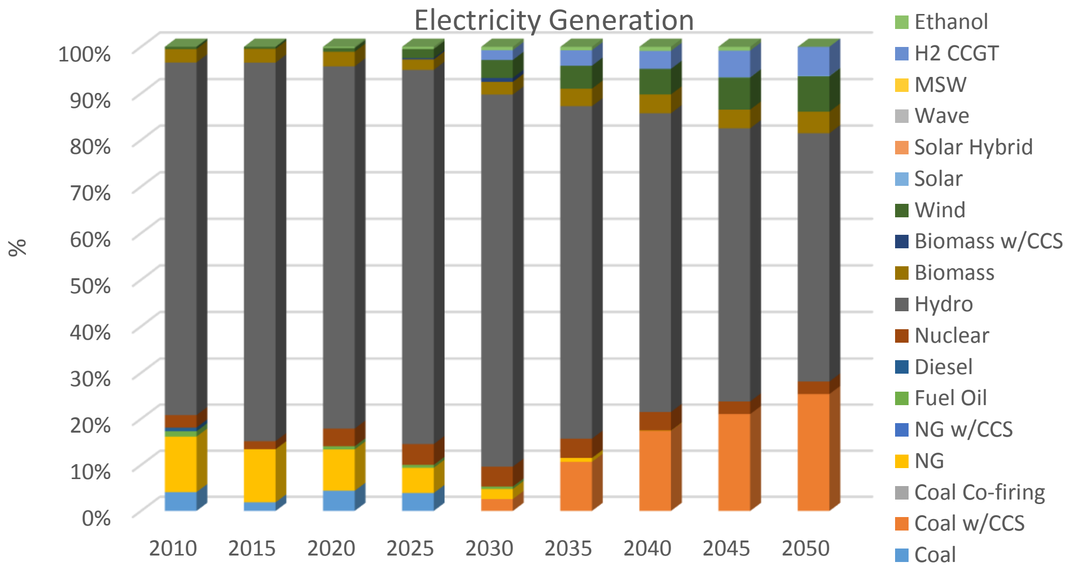

Figure A- 61 – Electricity Generation of scenario LC_MKTS_PF – %

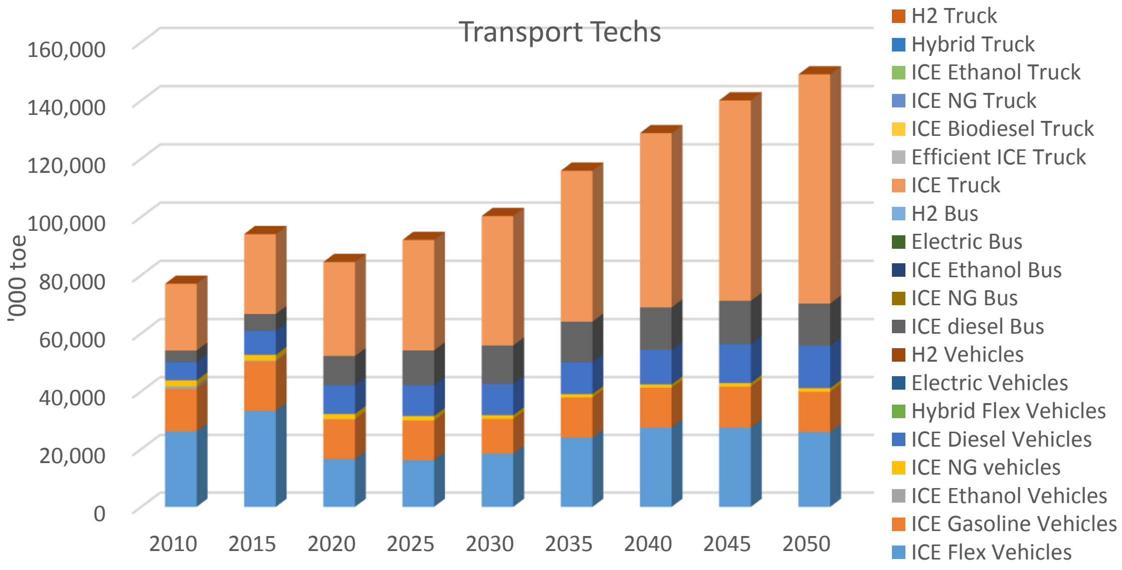

Figure A- 62 – Transport Sector Consumption of scenario LC_MKTS_PF – ktoe

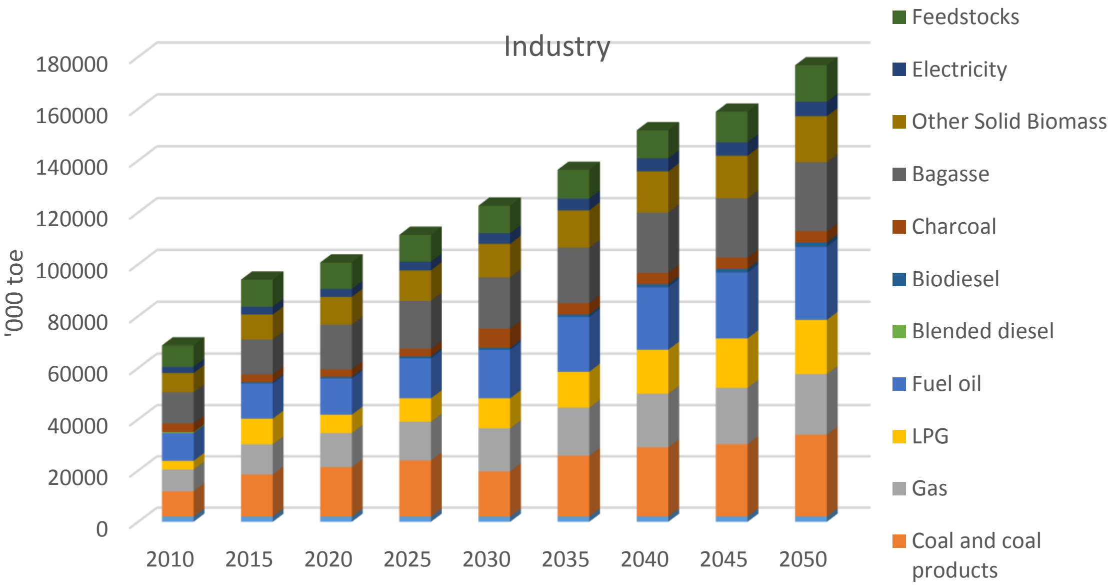

Figure A- 63 – Industry Consumption of scenario LC_MKTS_PF – ktoe

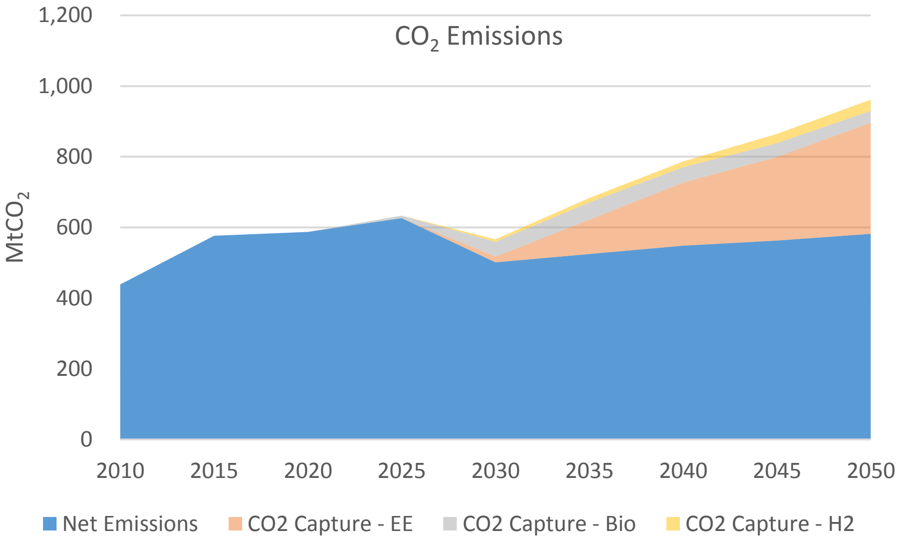

Figure A- 64 – CO_2 Emissions of scenario LC_MKTS_PF – $MtCO_2$

Scenario LC_MKTS_M

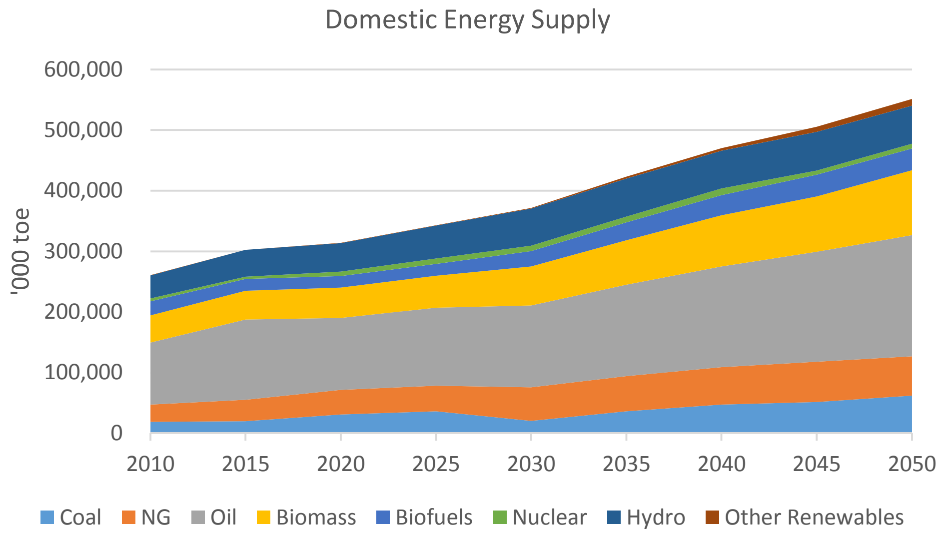

Figure A- 65 – Domestic Primary Energy Supply of scenario LC_MKTS_M – ktoe

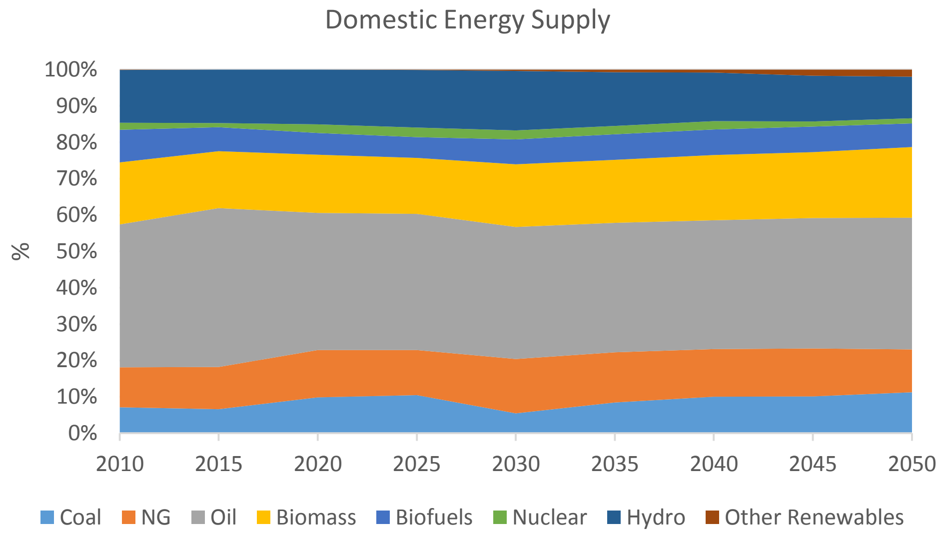

Figure A- 66 – Domestic Primary Energy Supply of scenario LC_MKTS_M - %

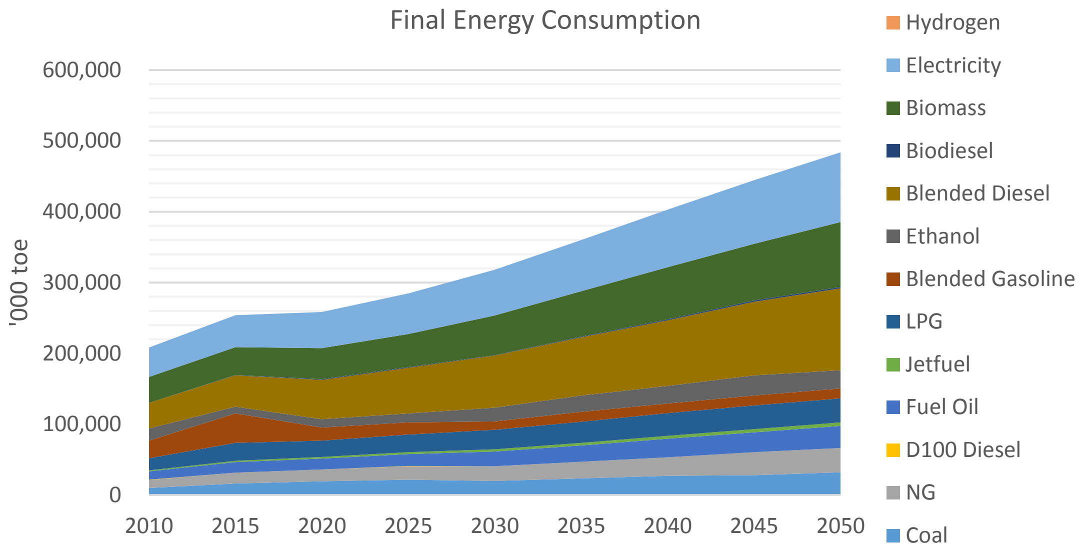

Figure A- 67 – Final Energy Consumption of scenario LC_MKTS_M – ktoe

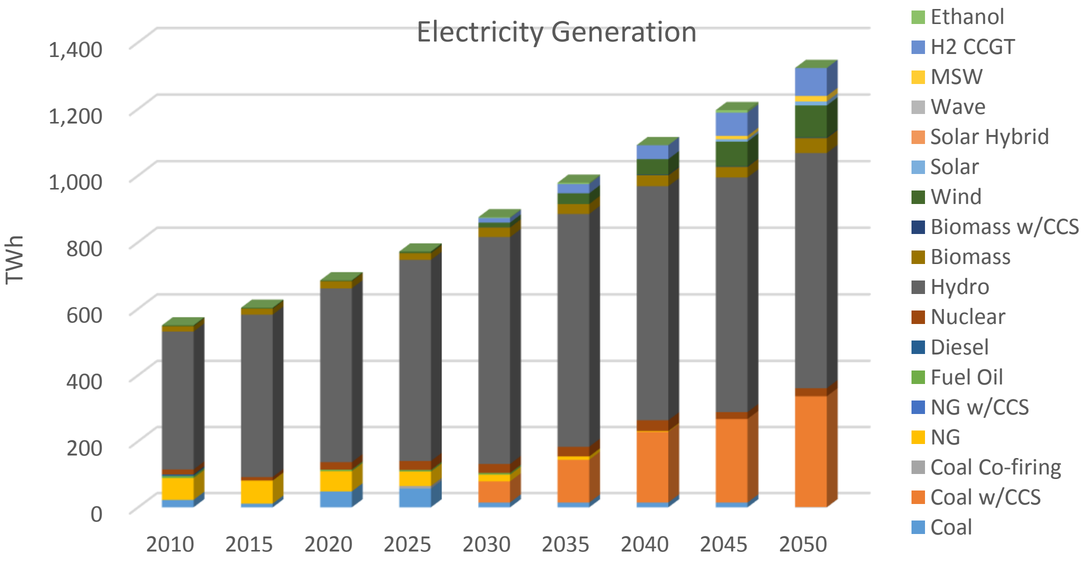

Figure A- 68 – Electricity Generation of scenario LC_MKTS_M – TWh

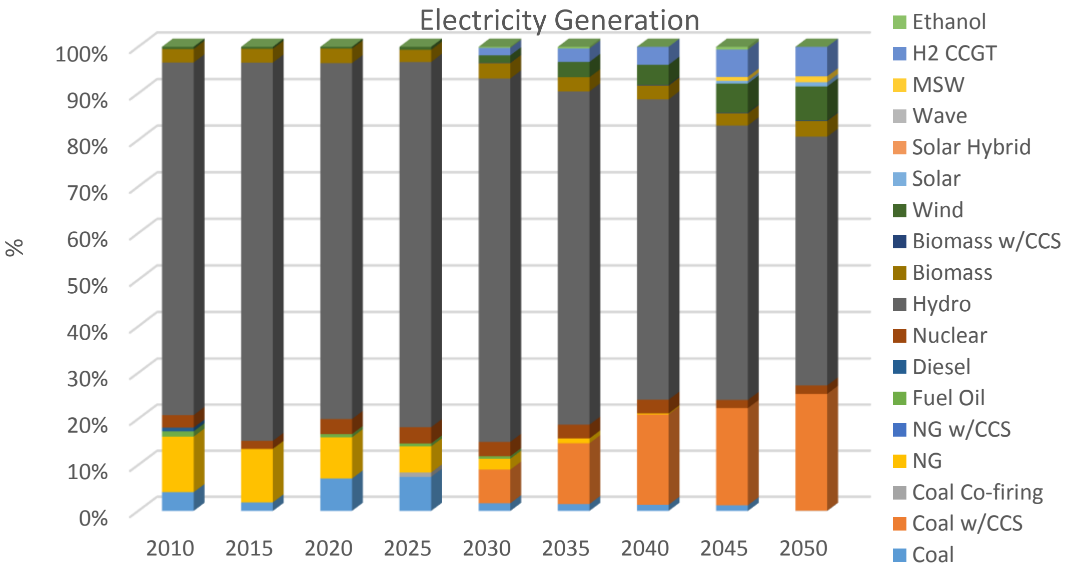

Figure A- 69 – Electricity Generation of scenario LC_MKTS_M – %

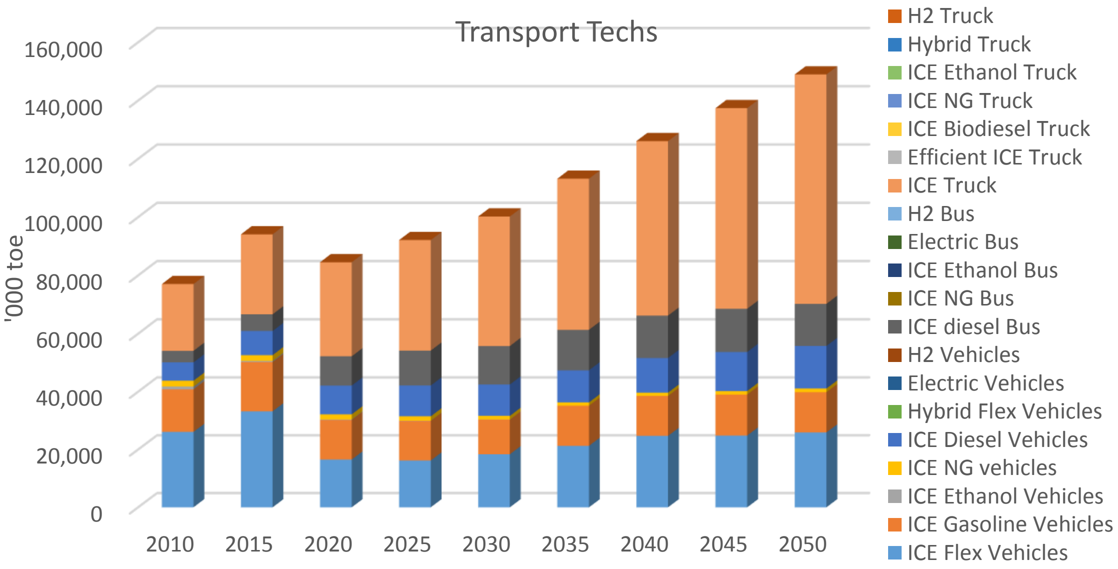

Figure A- 70 – Transport Sector Consumption of scenario LC_MKTS_M – ktoe

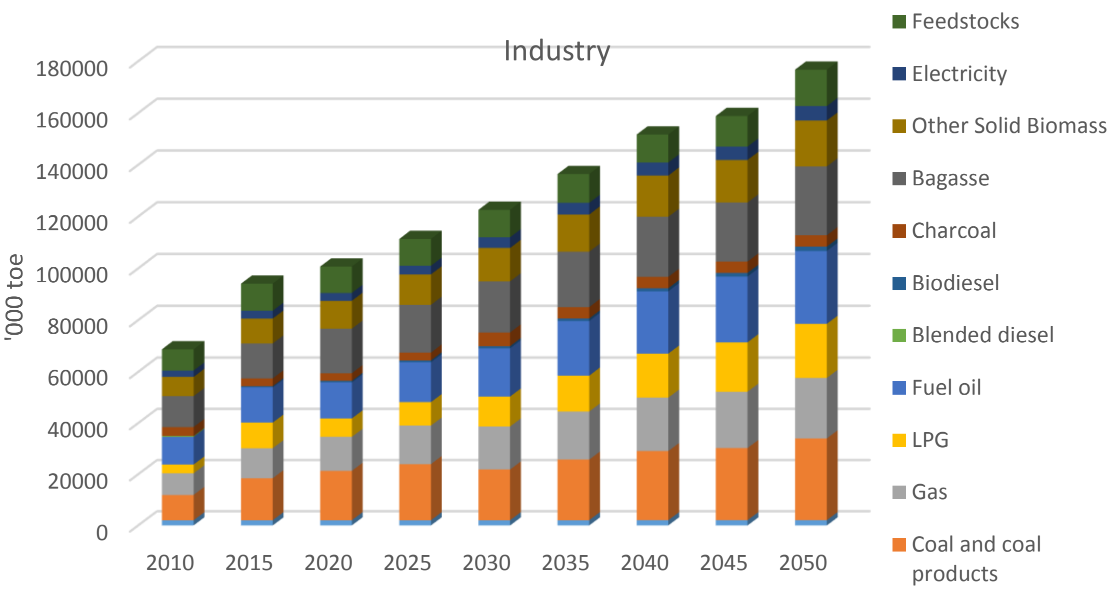

Figure A- 71 – Industry Consumption of scenario LC_MKTS_M – ktoe

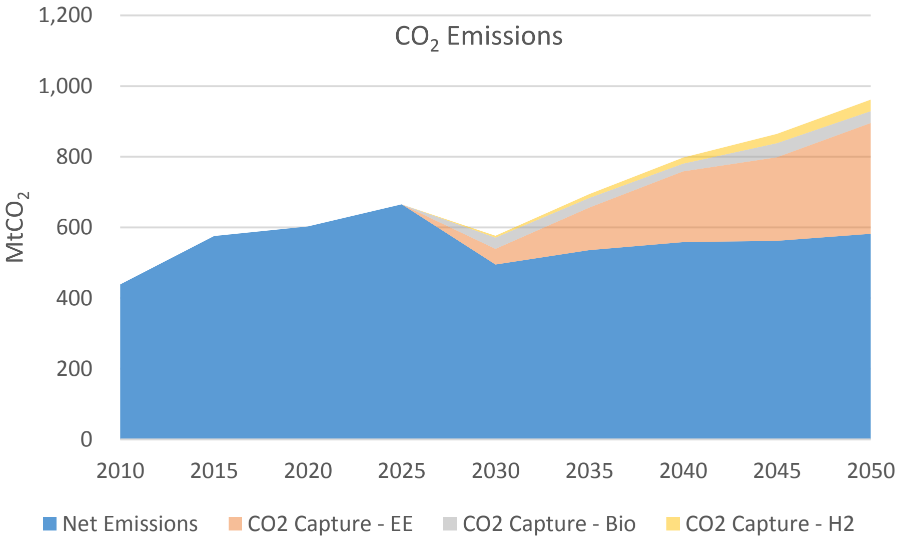

Figure A- 72 – CO_2 Emissions of scenario LC_MKTS_M – $MtCO_2$

Scenario LC_MKTS_PFD

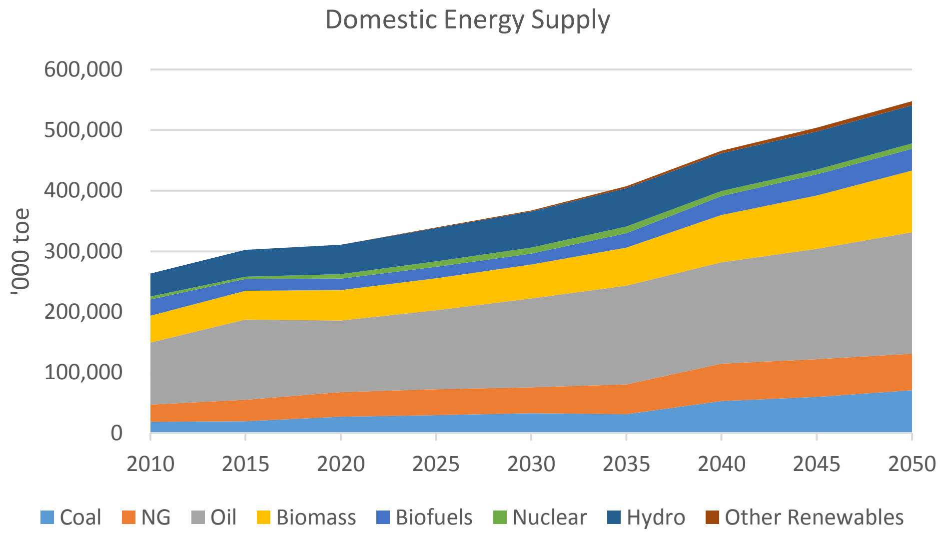

Figure A- 73 – Domestic Primary Energy Supply of scenario LC_MKTS_PFD – ktoe

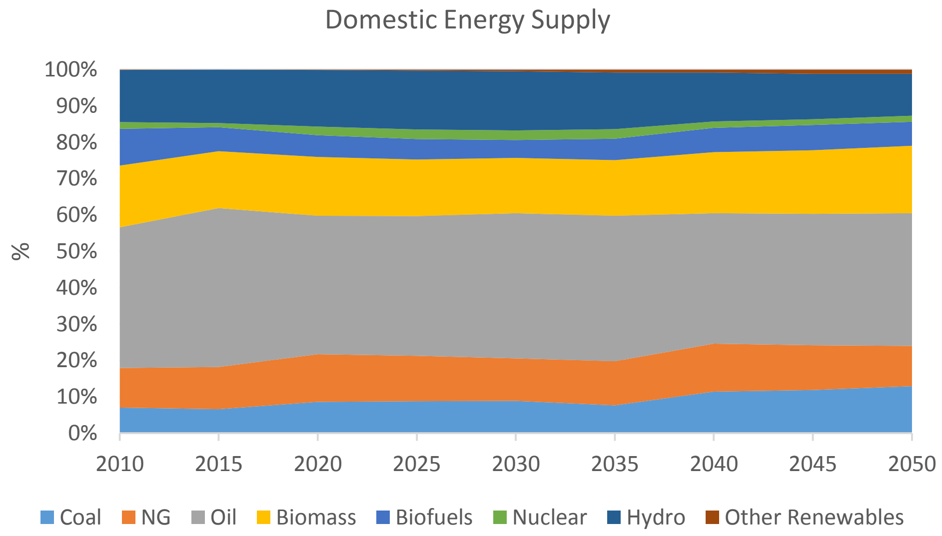

Figure A- 74 – Domestic Primary Energy Supply of scenario LC_MKTS_PFD - %

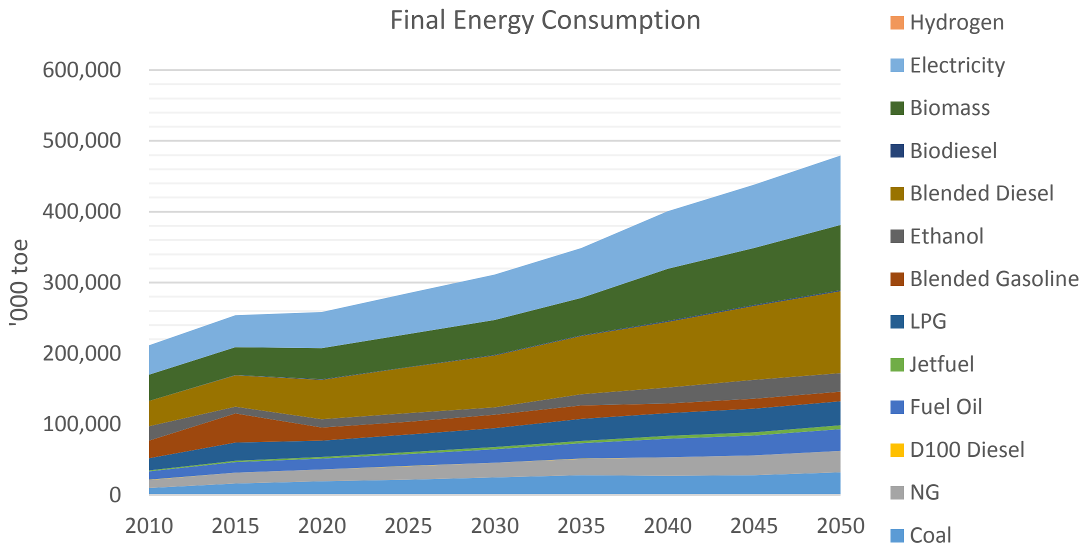

Figure A- 75 – Final Energy Consumption of scenario LC_MKTS_PFD – ktoe

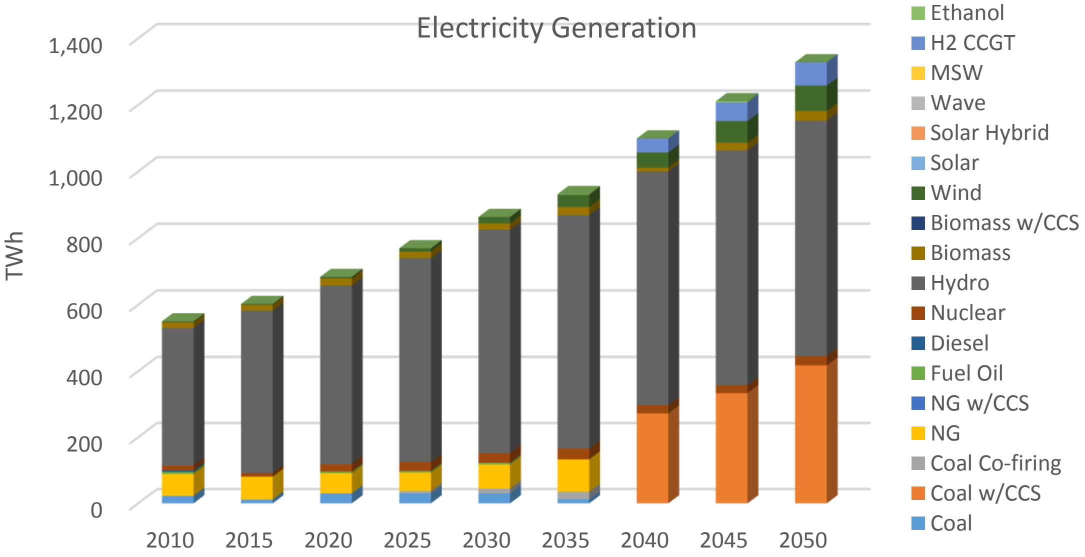

Figure A- 76 – Electricity Generation of scenario LC_MKTS_PFD – TWh

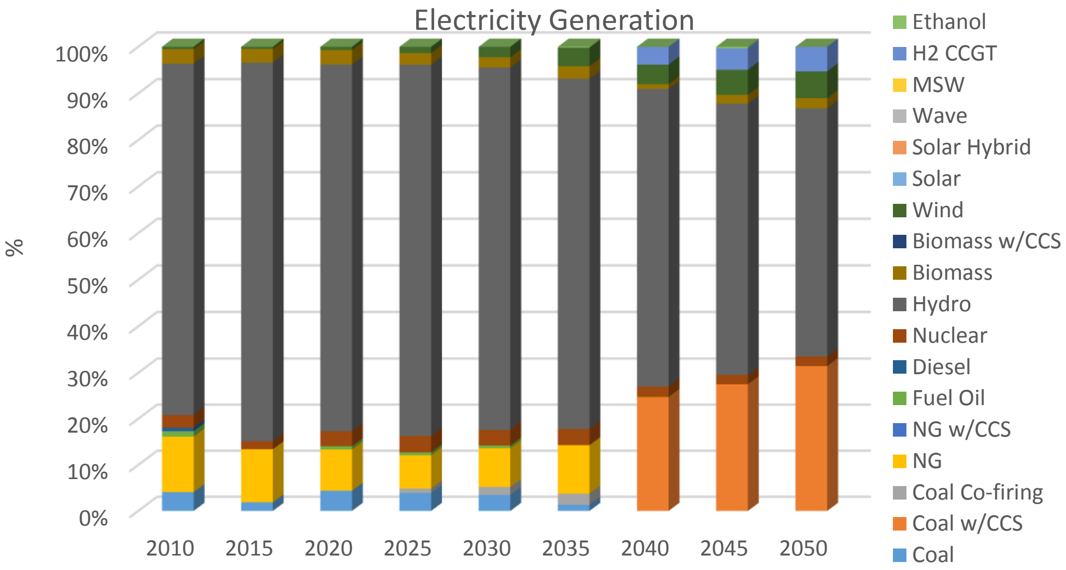

Figure A- 77 – Electricity Generation of scenario LC_MKTS_PFD – %

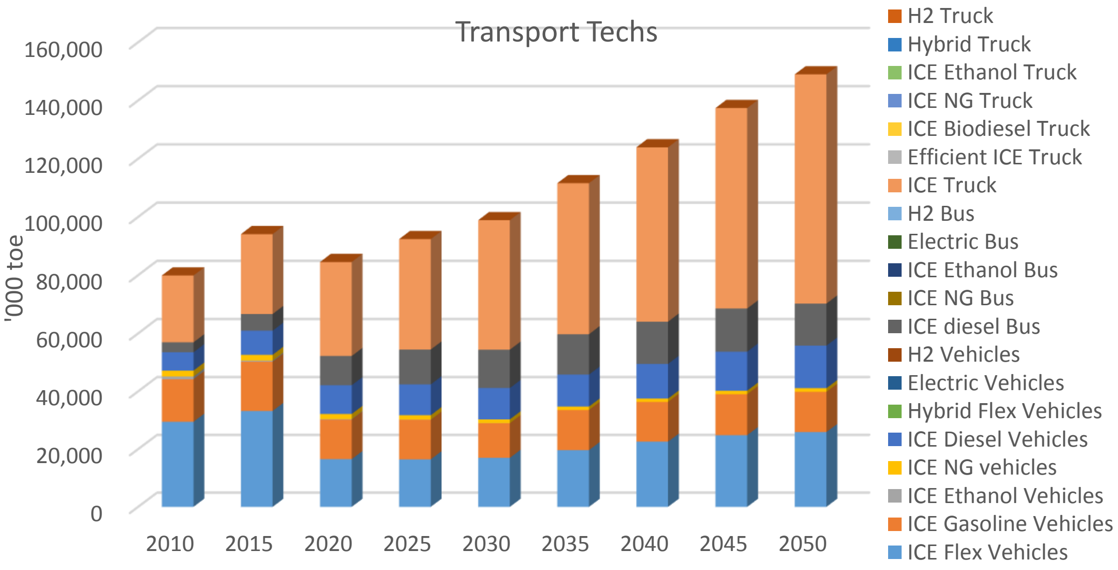

Figure A- 78 – Transport Sector Consumption of scenario LC_MKTS_PFD – ktoe

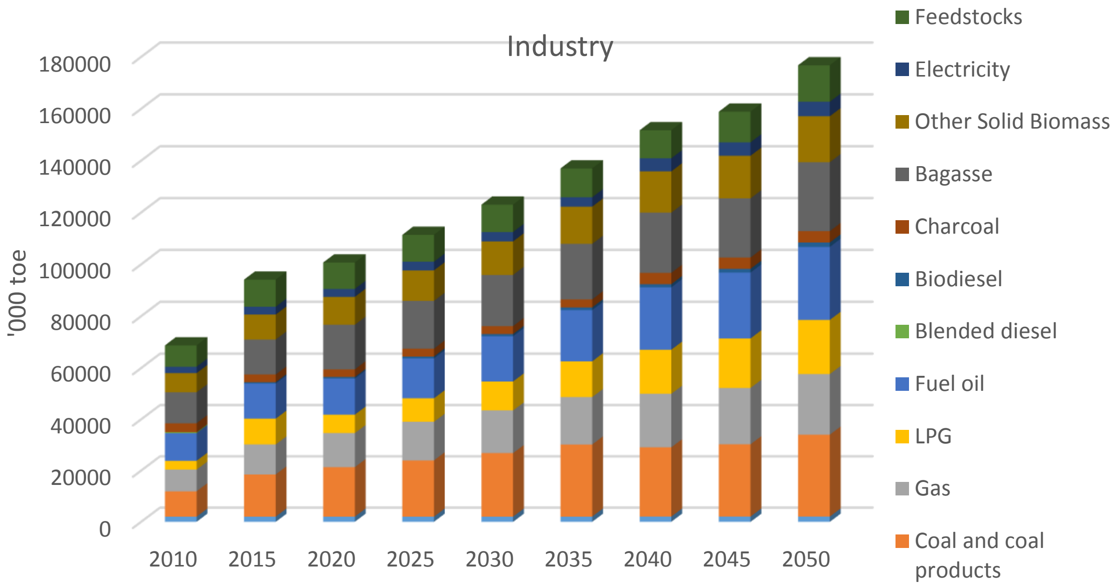

Figure A- 79 – Industry Consumption of scenario LC_MKTS_PFD – ktoe

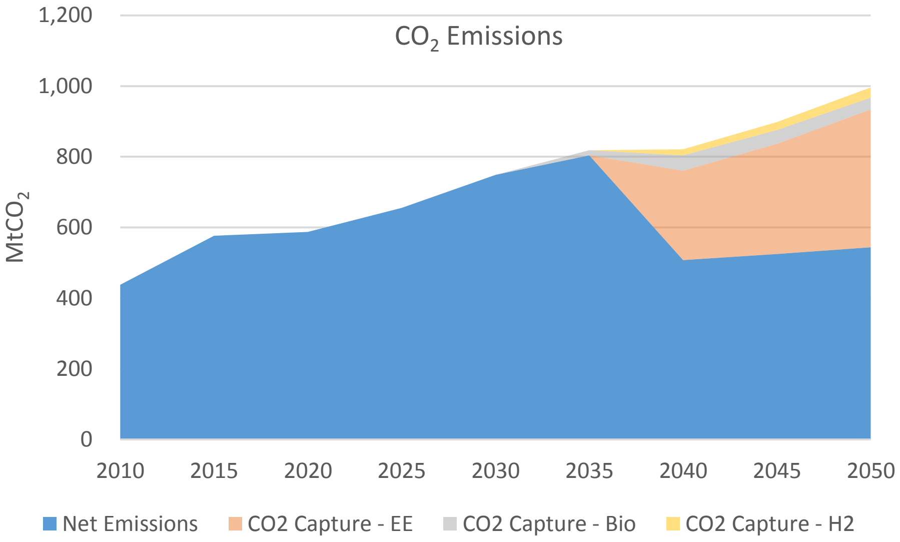

Figure A- 80 – CO_2 Emissions of scenario LC_MKTS_PFD – $MtCO_2$

Scenario LC_MKTS_MD

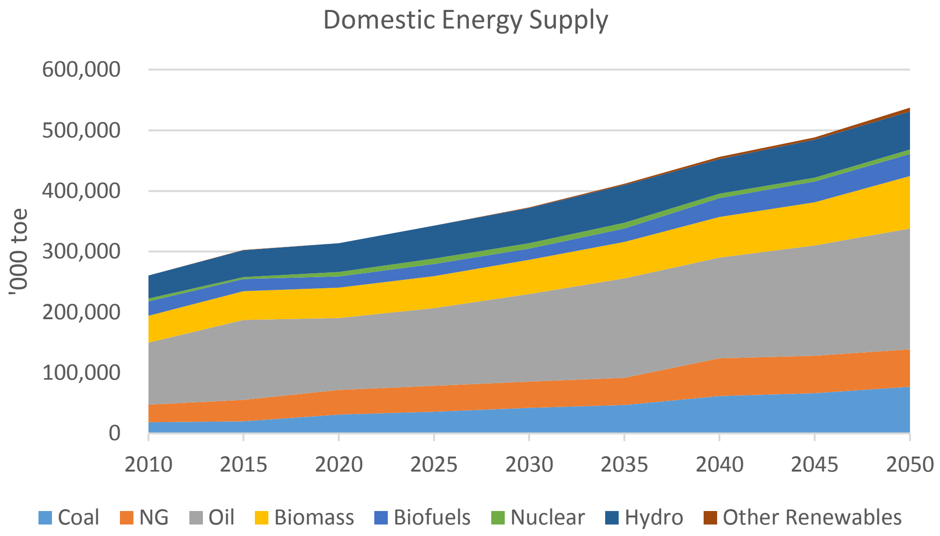

Figure A- 81 – Domestic Primary Energy Supply of scenario LC_MKTS_MD – ktoe

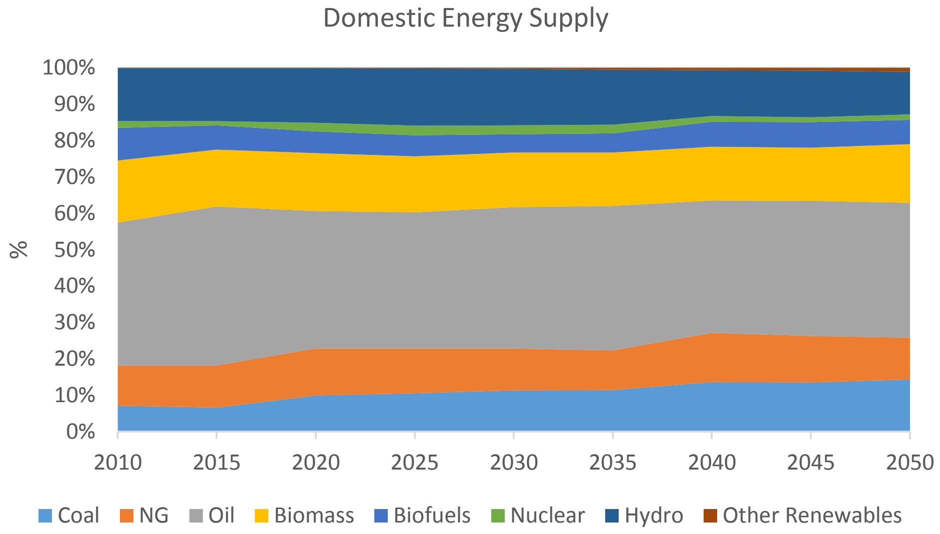

Figure A- 82 – Domestic Primary Energy Supply of scenario LC_MKTS_MD - %

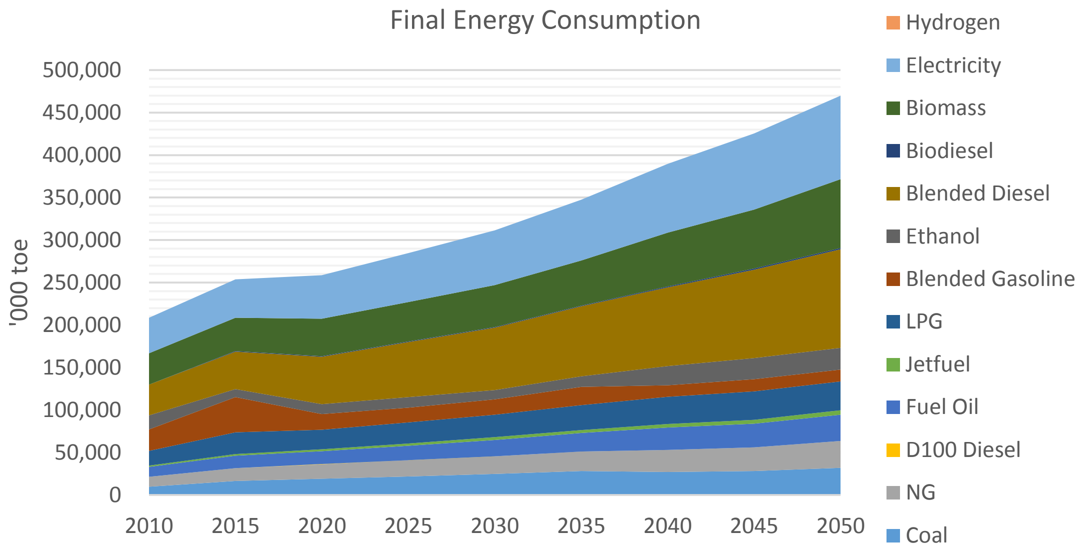

Figure A- 83 – Final Energy Consumption of scenario LC_MKTS_MD – ktoe

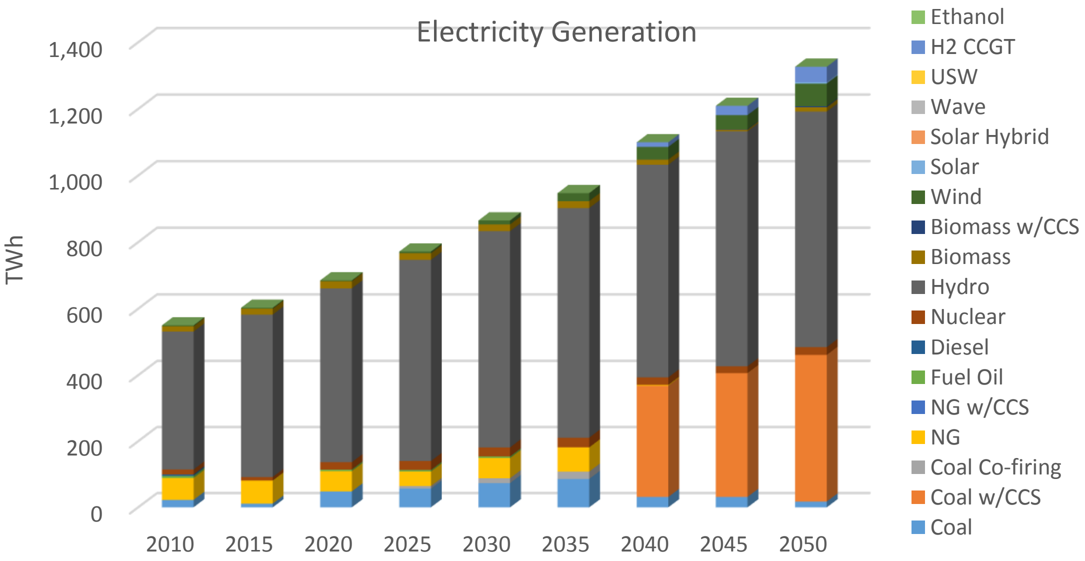

Figure A- 84 – Electricity Generation of scenario LC_MKTS_MD – TWh

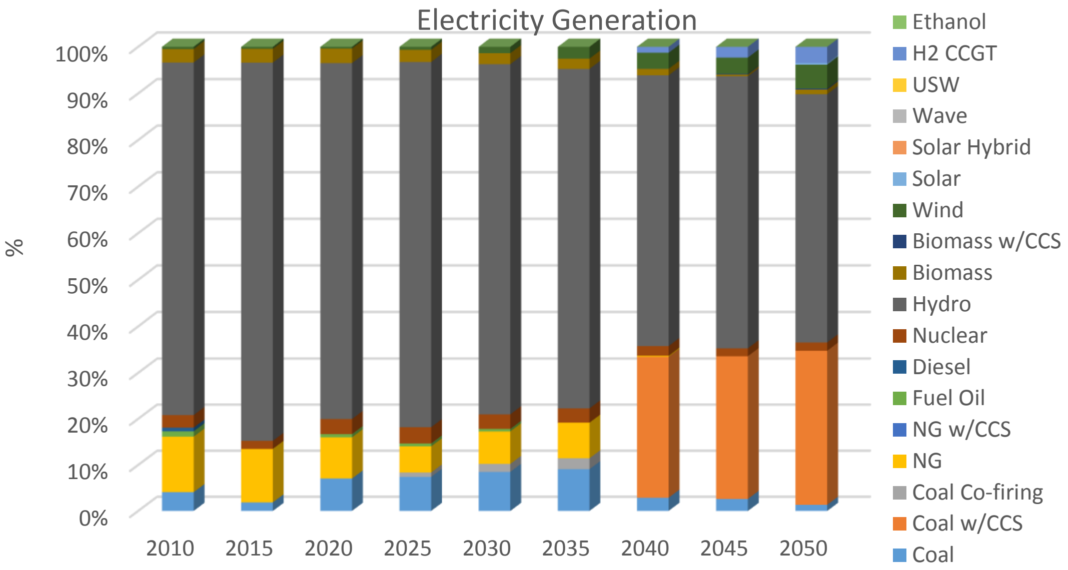

Figure A- 85 – Electricity Generation of scenario LC_MKTS_MD – %

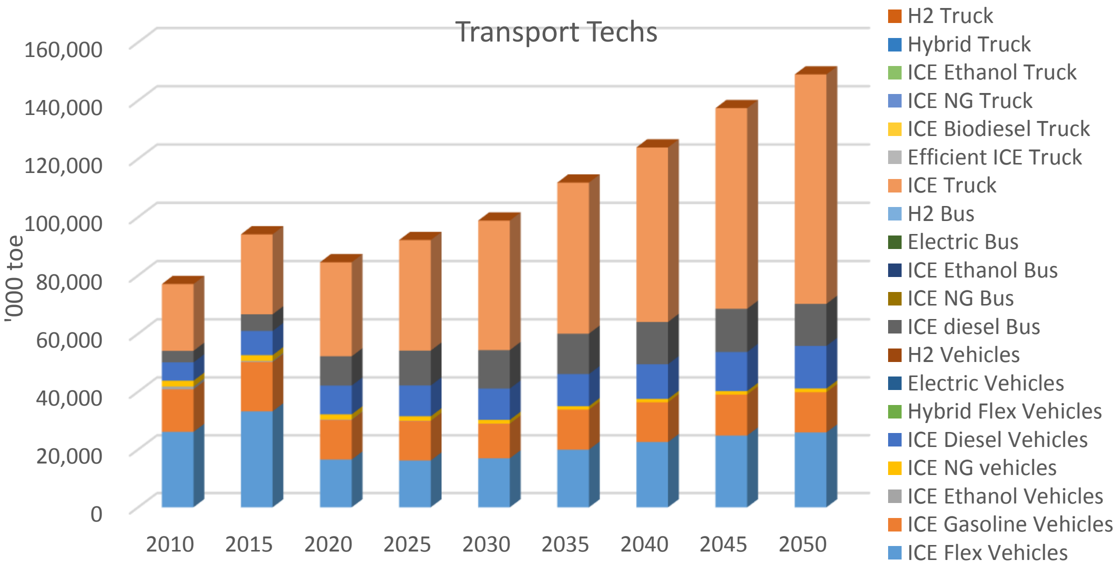

Figure A- 86 – Transport Sector Consumption of scenario LC_MKTS_MD – ktoe

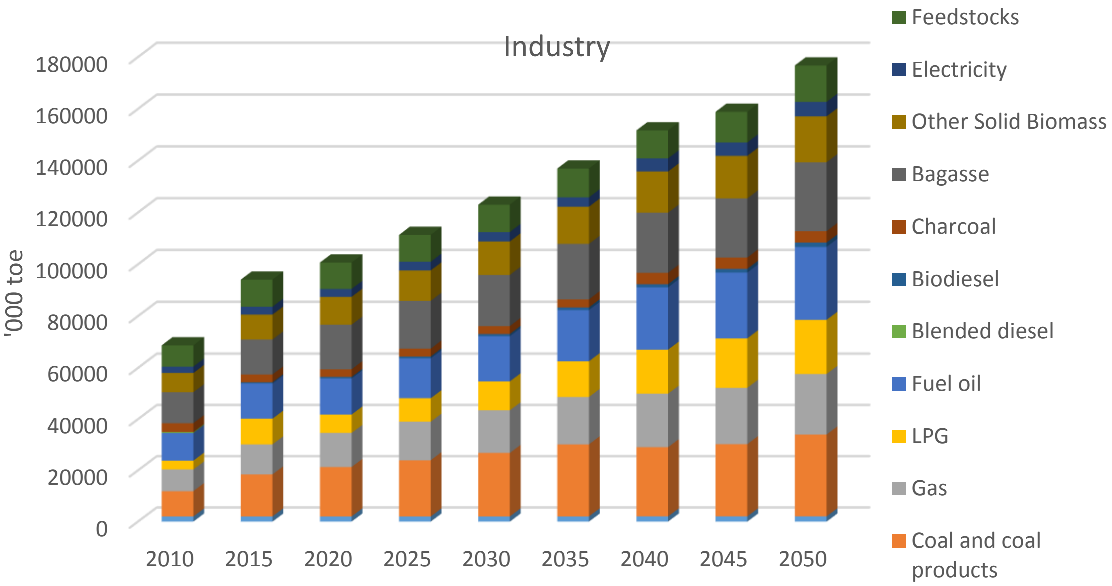

Figure A- 87 – Industry Consumption of scenario LC_MKTS_MD – ktoe

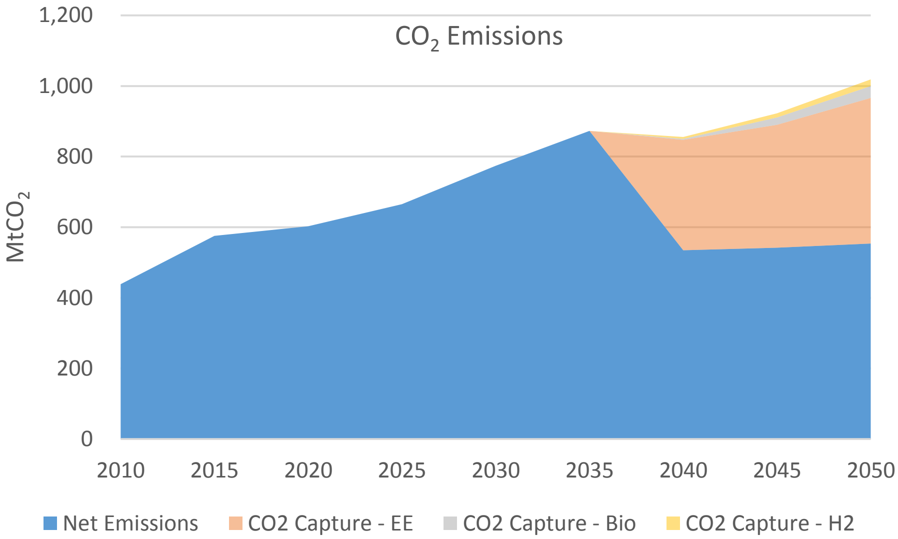

Figure A- 88 – CO_2 Emissions of scenario LC_MKTS_MD – $MtCO_2$

Scenario BASE_DDRS

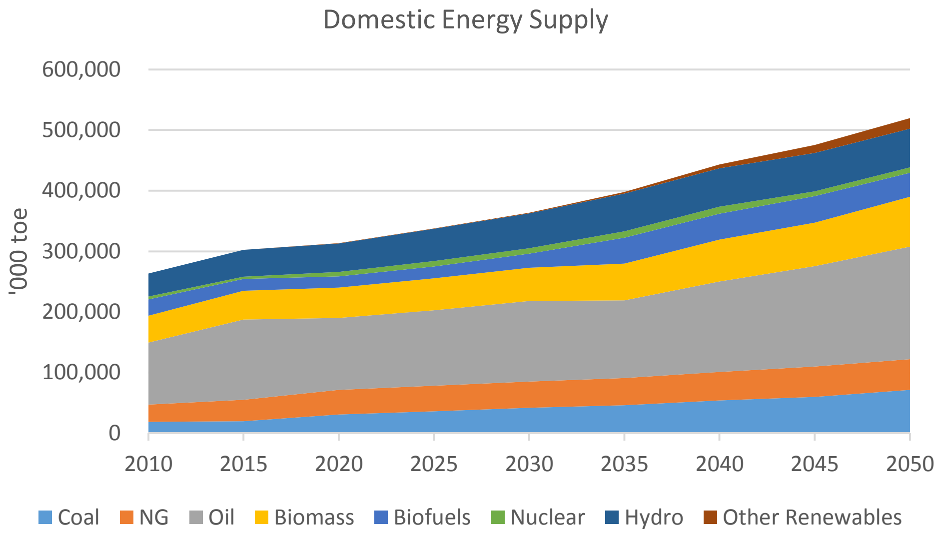

Figure A- 89 – Domestic Primary Energy Supply of scenario BASE_DDRS – ktoe

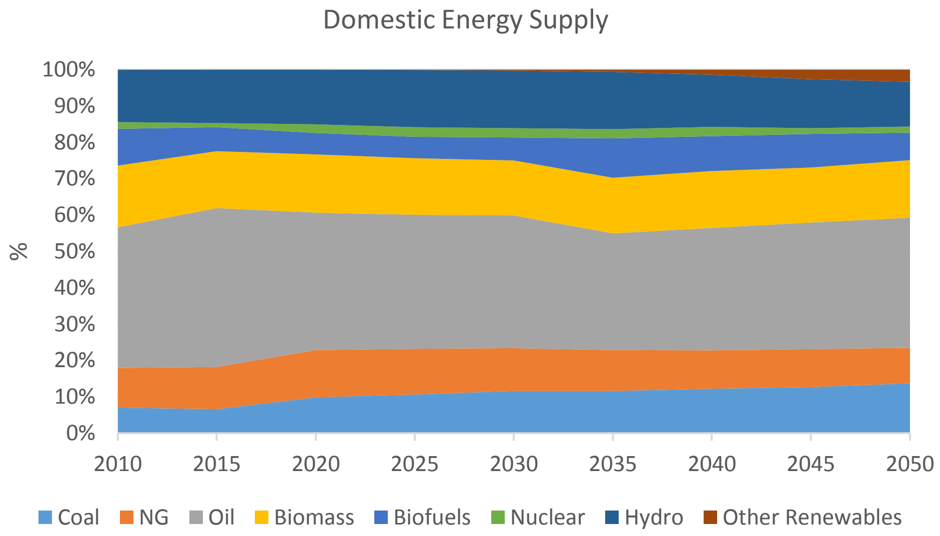

Figure A- 90 – Domestic Primary Energy Supply of scenario BASE_ DDRS - %

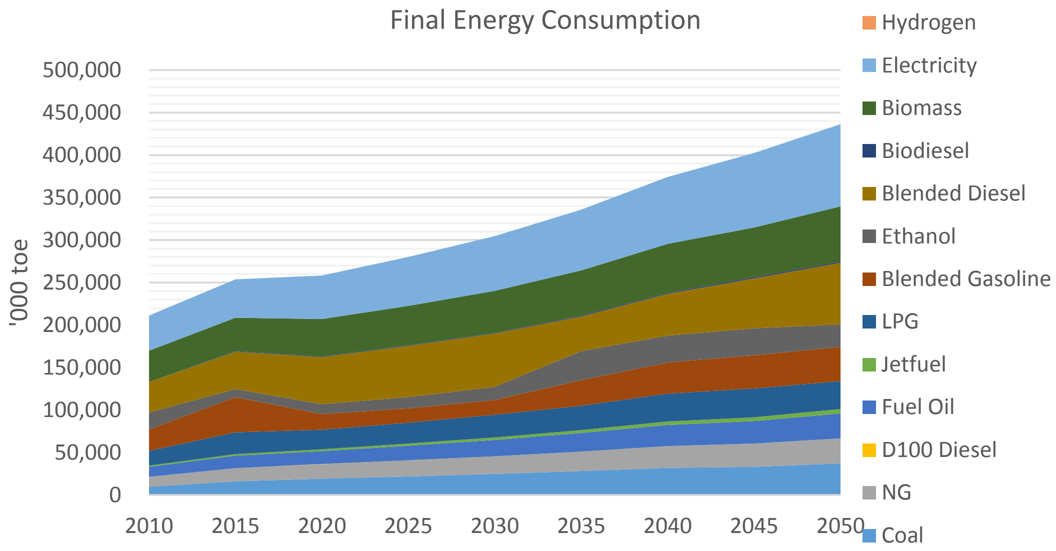

Figure A- 91 – Final Energy Consumption of scenario BASE_ DDRS – ktoe

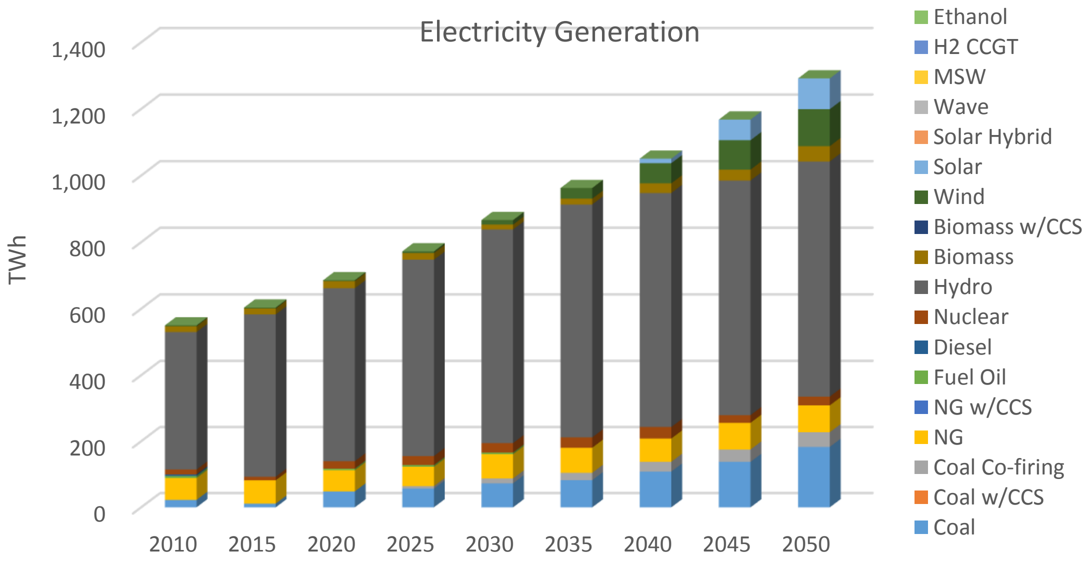

Figure A- 92 – Electricity Generation of scenario BASE_ DDRS – TWh

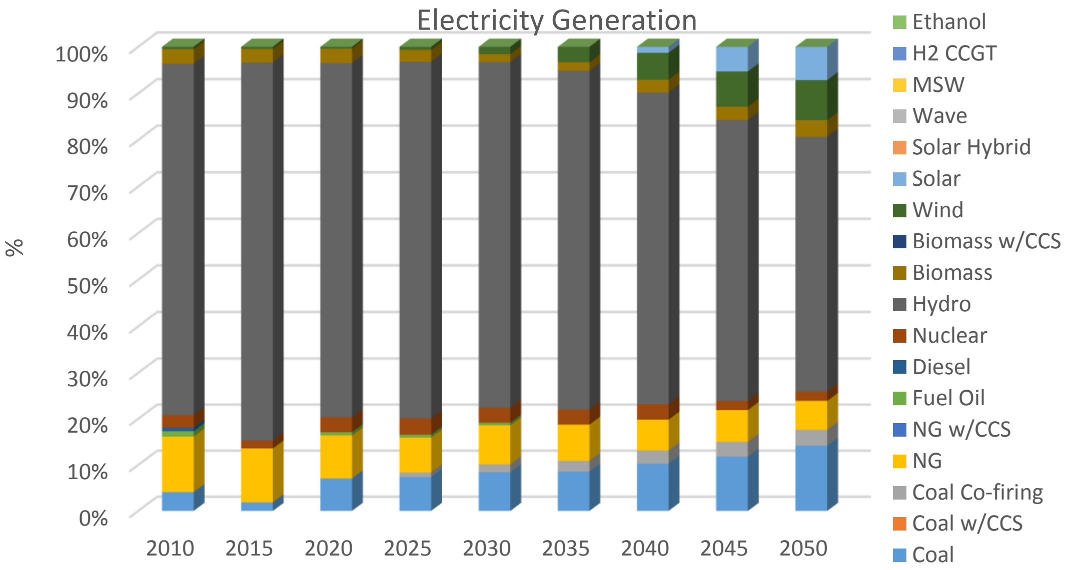

Figure A- 93 – Electricity Generation of scenario BASE_ DDRS – %

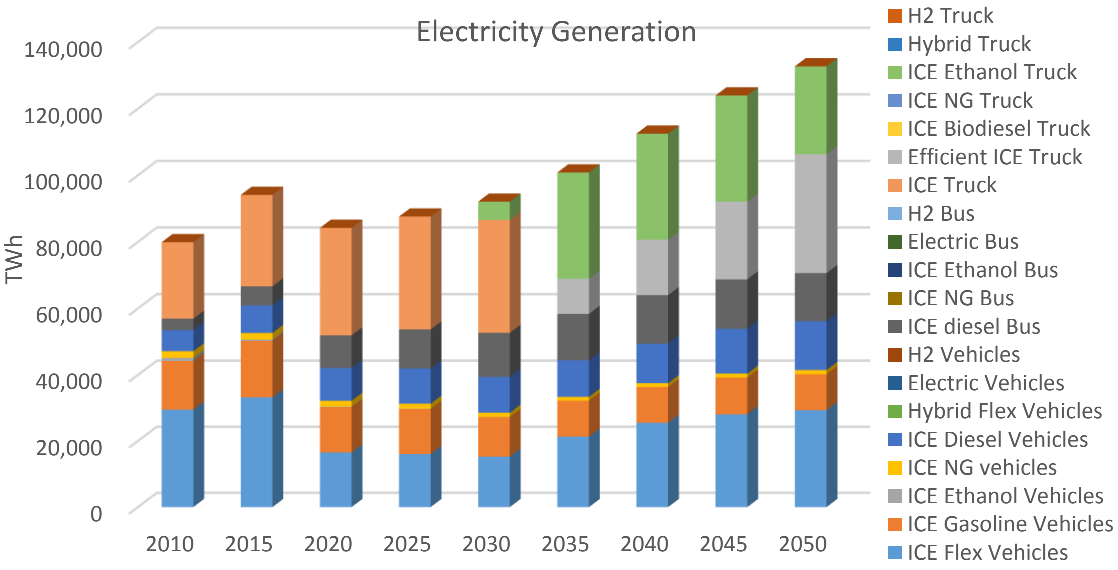

Figure A- 94 – Transport Sector Consumption of scenario BASE_ DDRS – ktoe

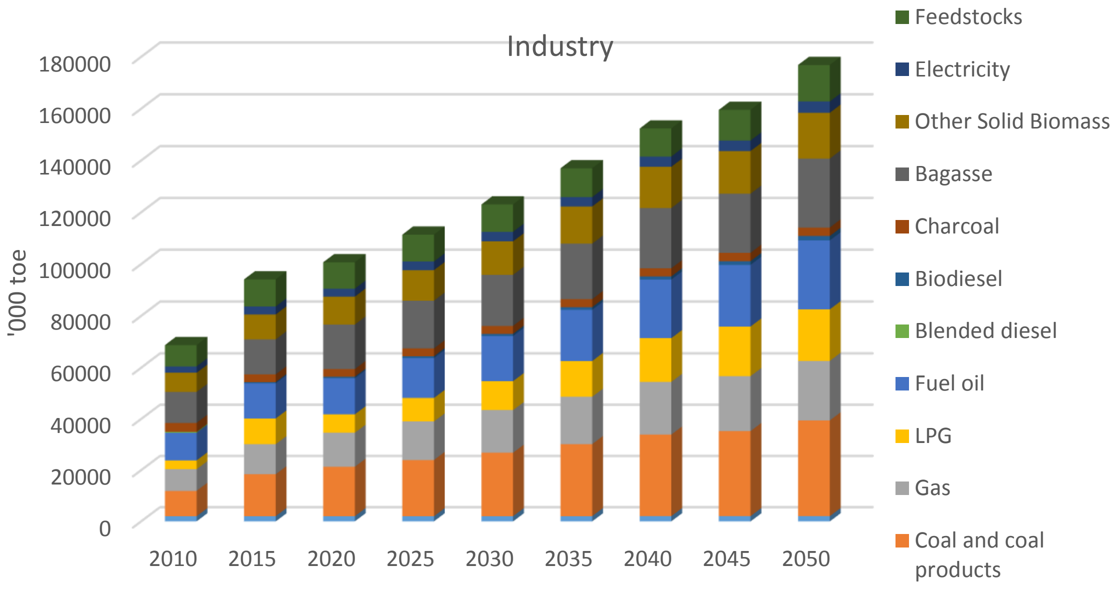

Figure A- 95 – Industry Consumption of scenario BASE_ DDRS – ktoe

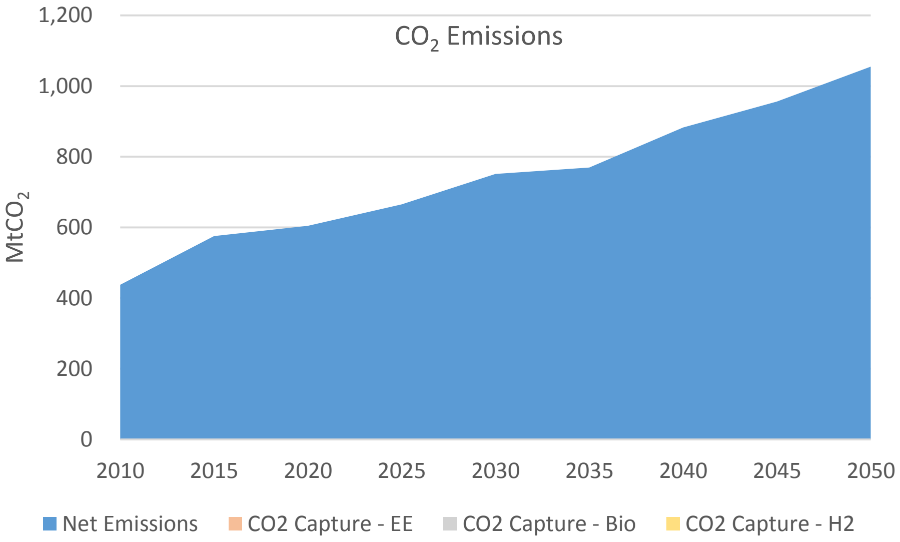

Figure A- 96 – CO$_2$ Emissions of scenario BASE_ DDRS – MtCO$_2$

Scenario LC_DDRS_PF

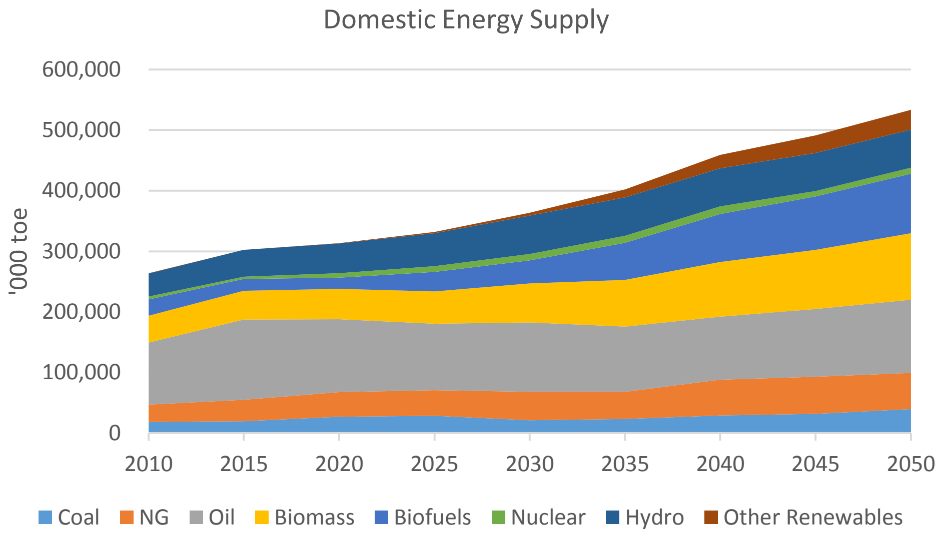

Figure A- 97 – Domestic Primary Energy Supply of scenario LC_ DDRS_PF – ktoe

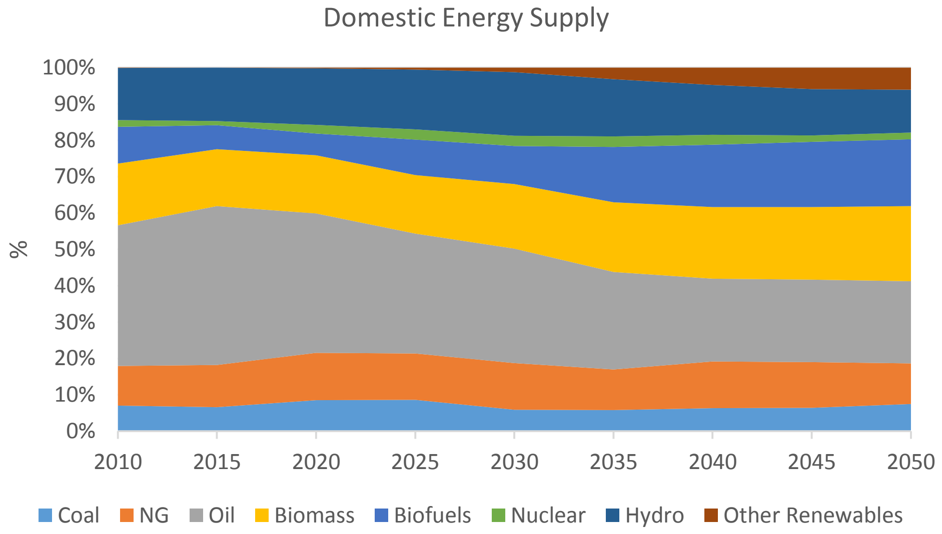

Figure A- 98 – Domestic Primary Energy Supply of scenario LC_ DDRS_PF - %

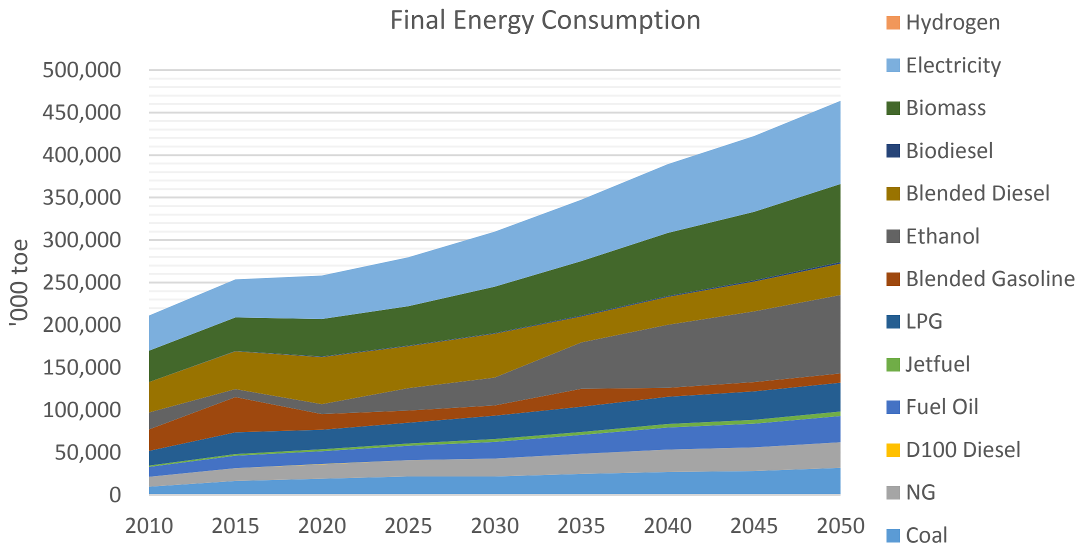

Figure A- 99 – Final Energy Consumption of scenario LC_ DDRS_PF – ktoe

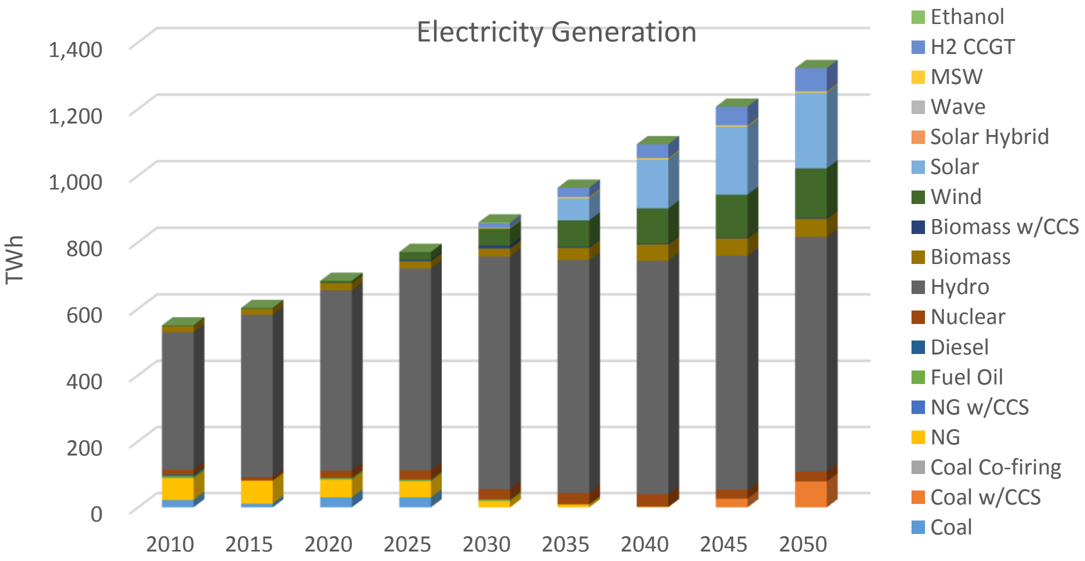

Figure A- 100 – Electricity Generation of scenario LC_ DDRS_PF – TWh

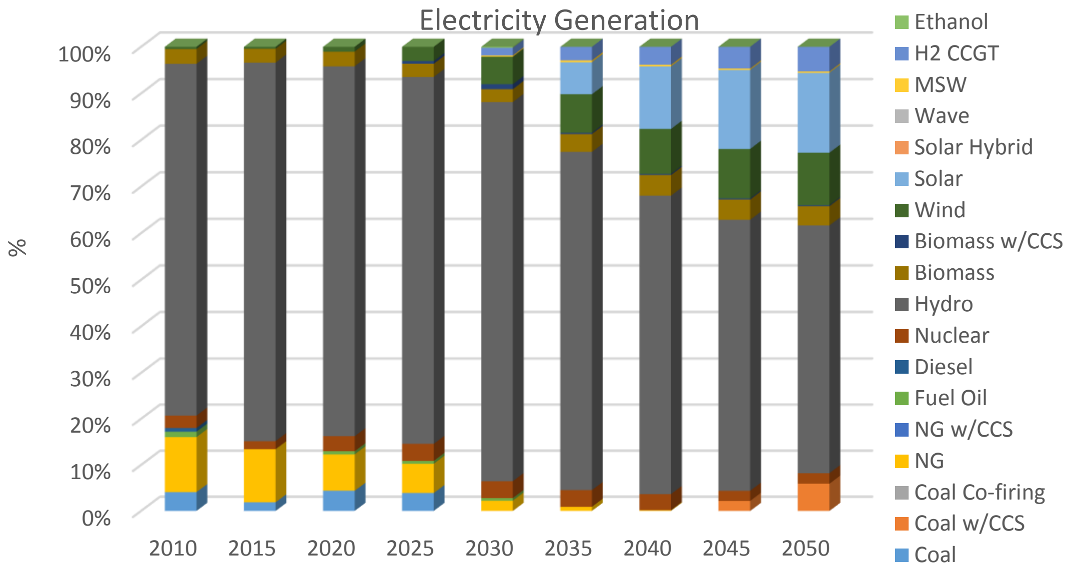

Figure A- 101 – Electricity Generation of scenario LC_ DDRS_PF – %

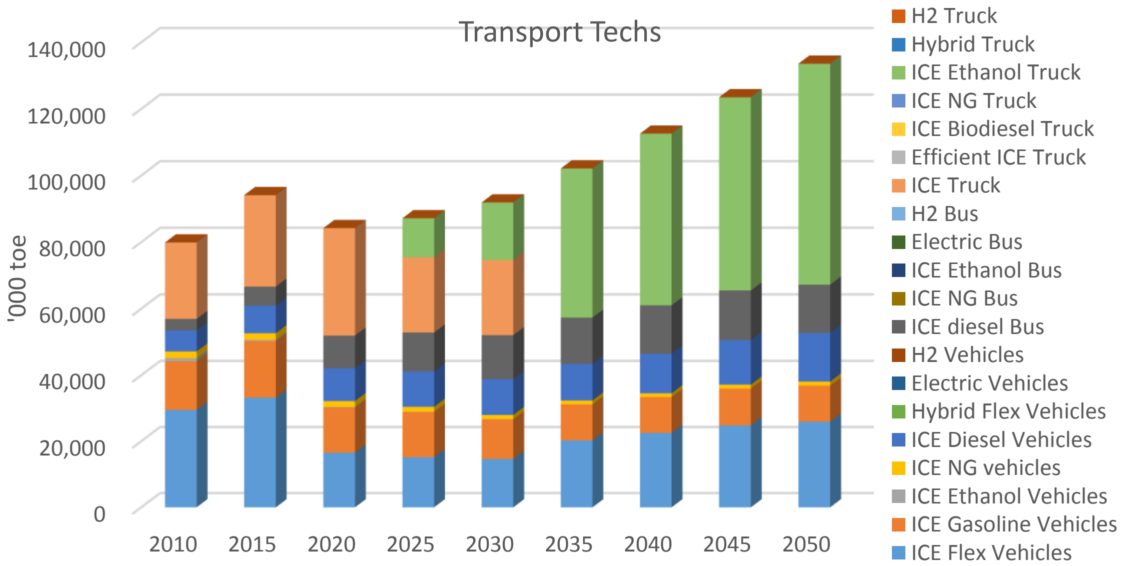

Figure A- 102 – Transport Sector Consumption of scenario LC_ DDRS_PF – ktoe

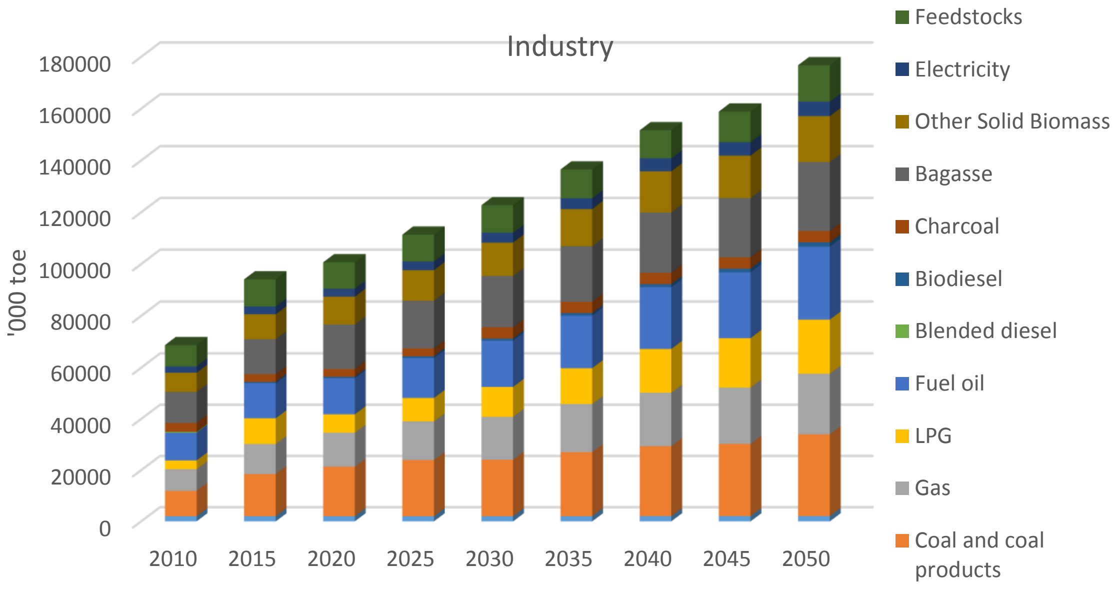

Figure A- 103 – Industry Consumption of scenario LC_ DDRS_PF – ktoe

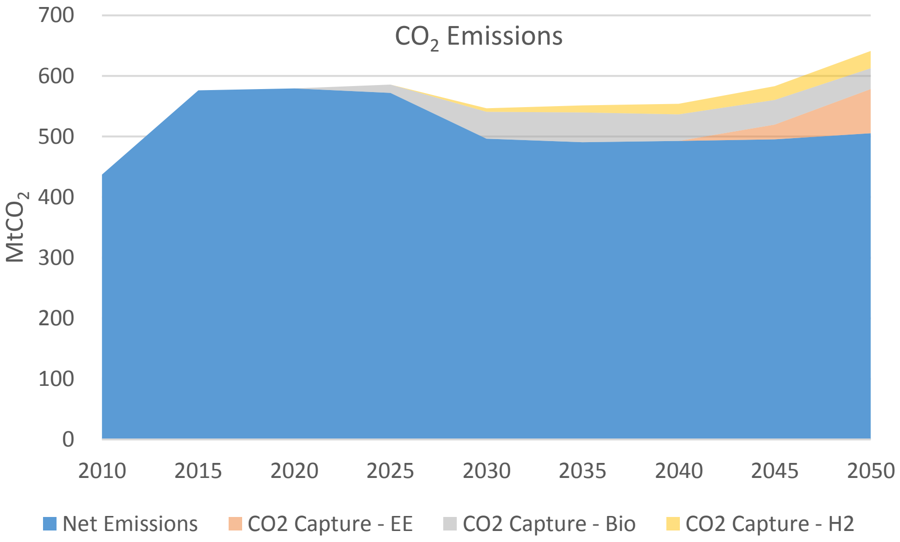

Figure A- 104 – CO_2 Emissions of scenario LC_ DDRS_PF – $MtCO_2$

Scenario LC_DDRS_M

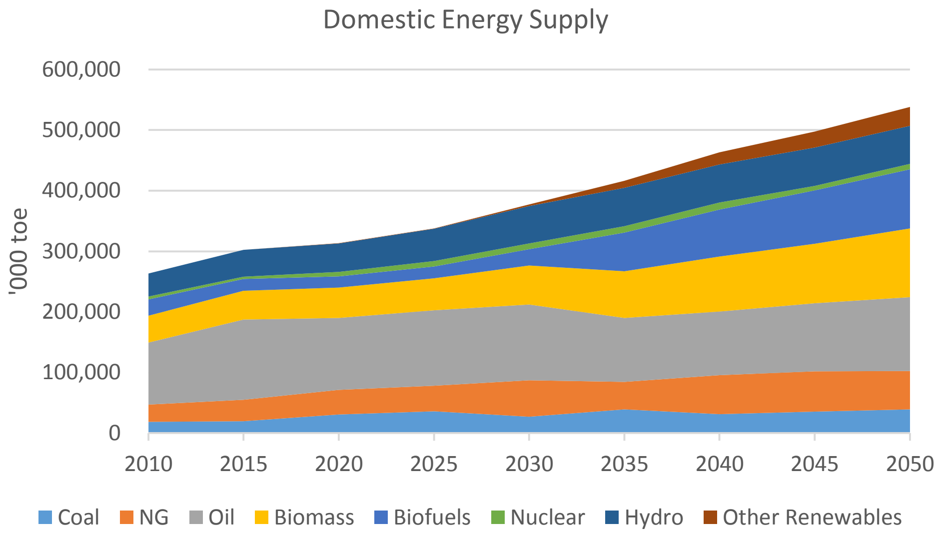

Figure A- 105 – Domestic Primary Energy Supply of scenario LC_DDRS_M – ktoe

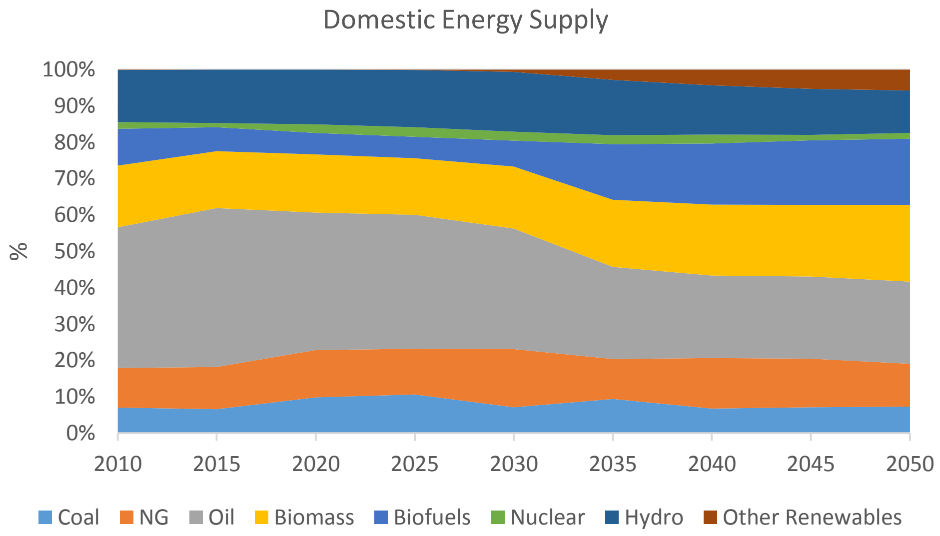

Figure A- 106 – Domestic Primary Energy Supply of scenario LC_DDRS_M - %

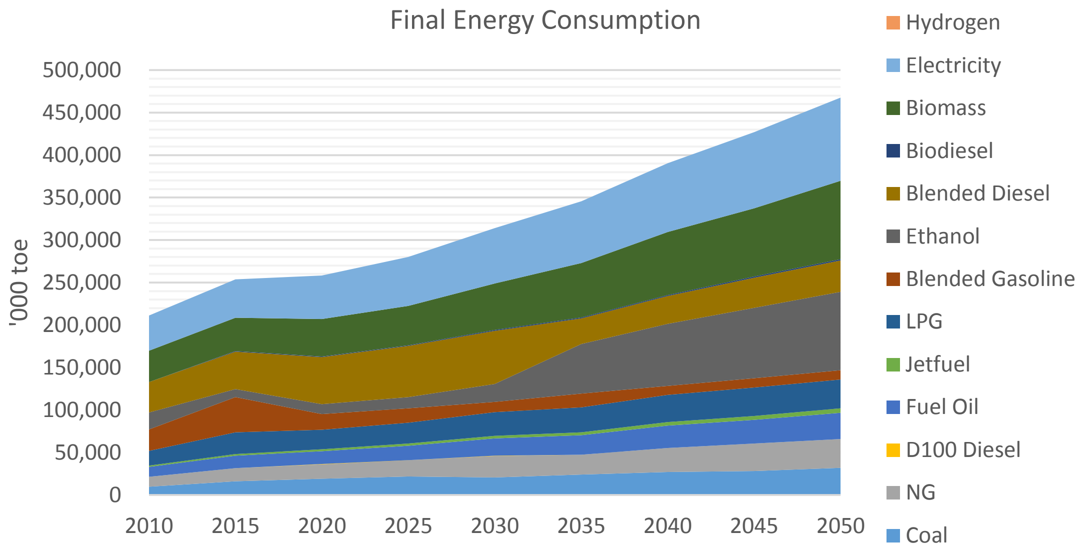

Figure A- 107 – Final Energy Consumption of scenario LC_DDRS_M – ktoe

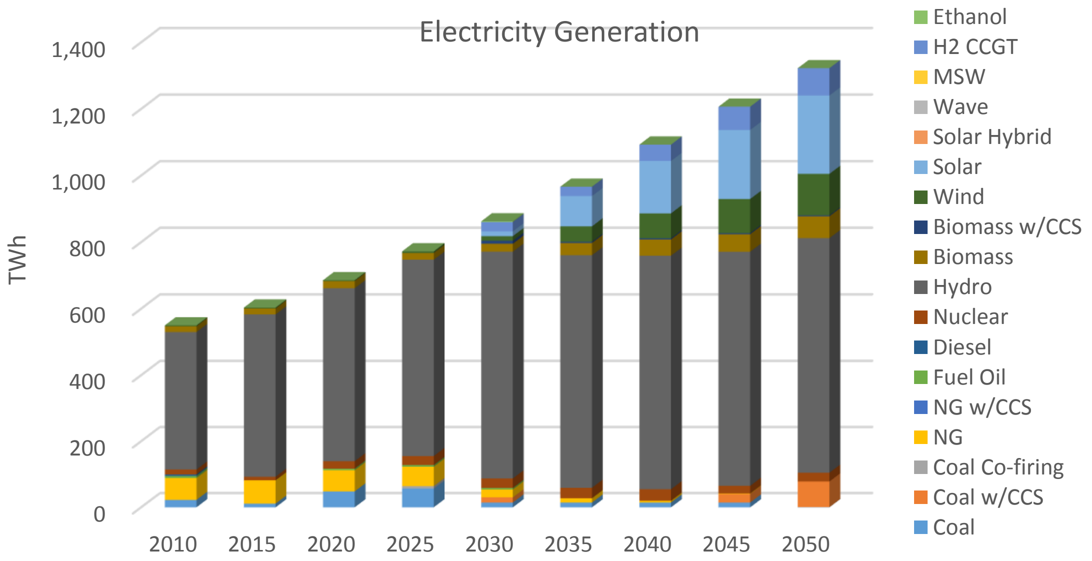

Figure A- 108 – Electricity Generation of scenario LC_DDRS_M – TWh

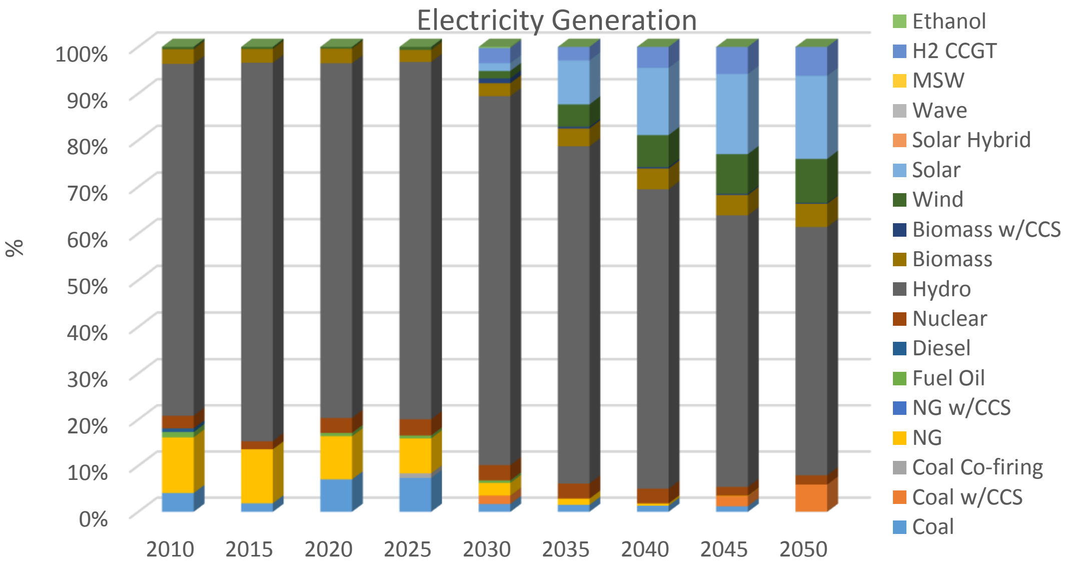

Figure A- 109 – Electricity Generation of scenario LC_DDRS_M – %

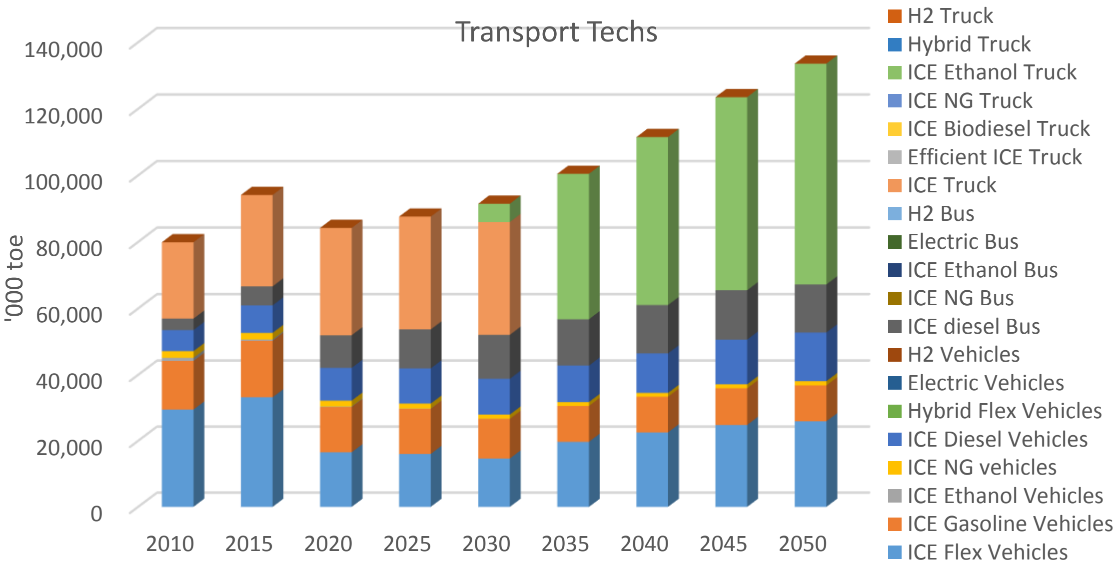

Figure A- 110 – Transport Sector Consumption of scenario LC_DDRS_M – ktoe

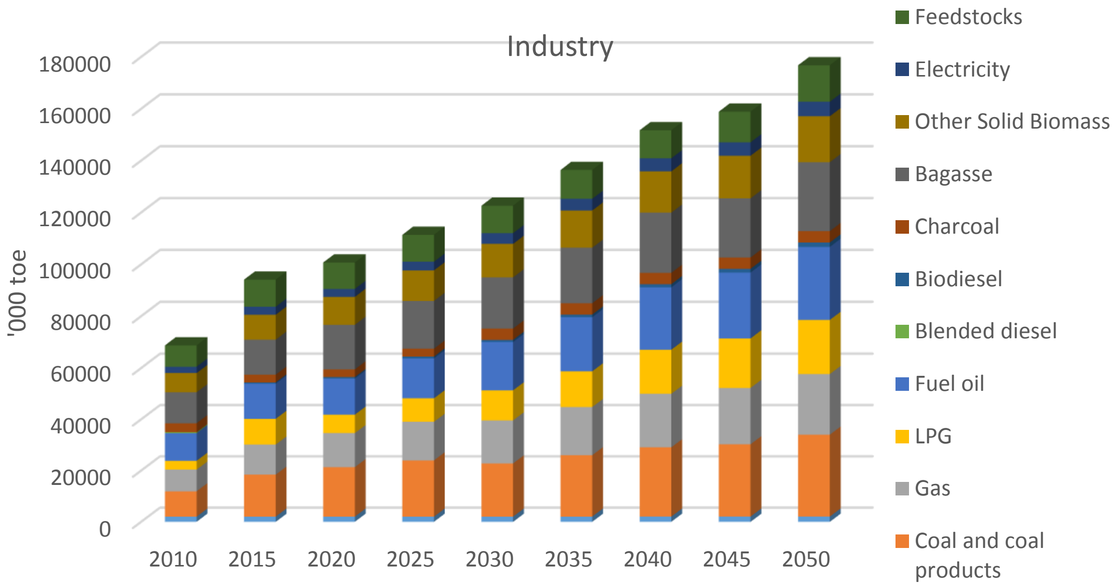

Figure A- 111 – Industry Consumption of scenario LC_DDRS_M – ktoe

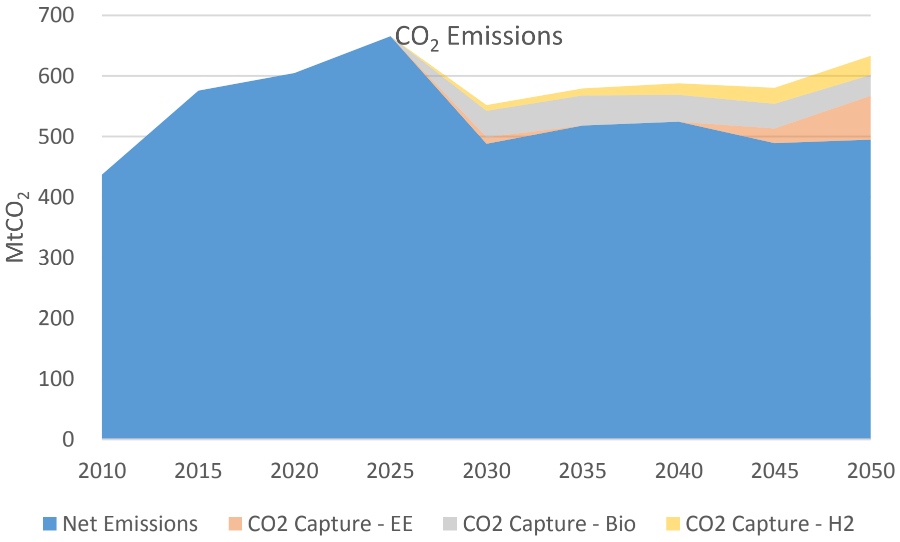

Figure A- 112 – CO$_2$ Emissions of scenario LC_DDRS_M – MtCO$_2$

Scenario LC_DDRS_PFD

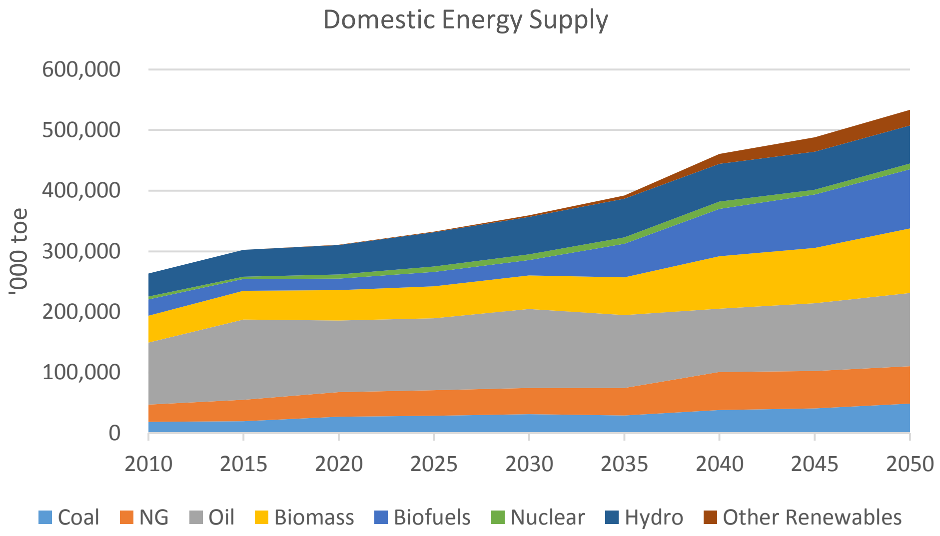

Figure A- 113 – Domestic Primary Energy Supply of scenario LC_DDRS_PFD – ktoe

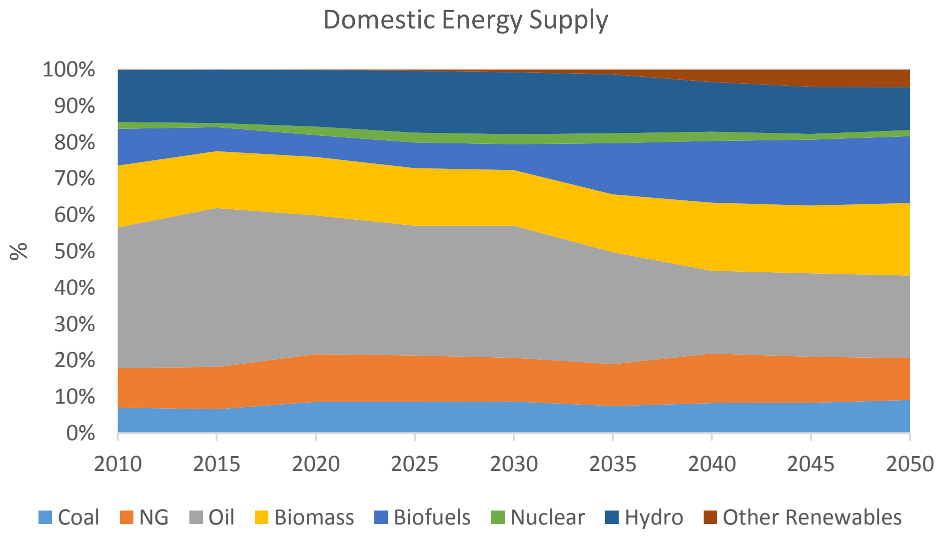

Figure A- 114 – Domestic Primary Energy Supply of scenario LC_DDRS_PFD - %

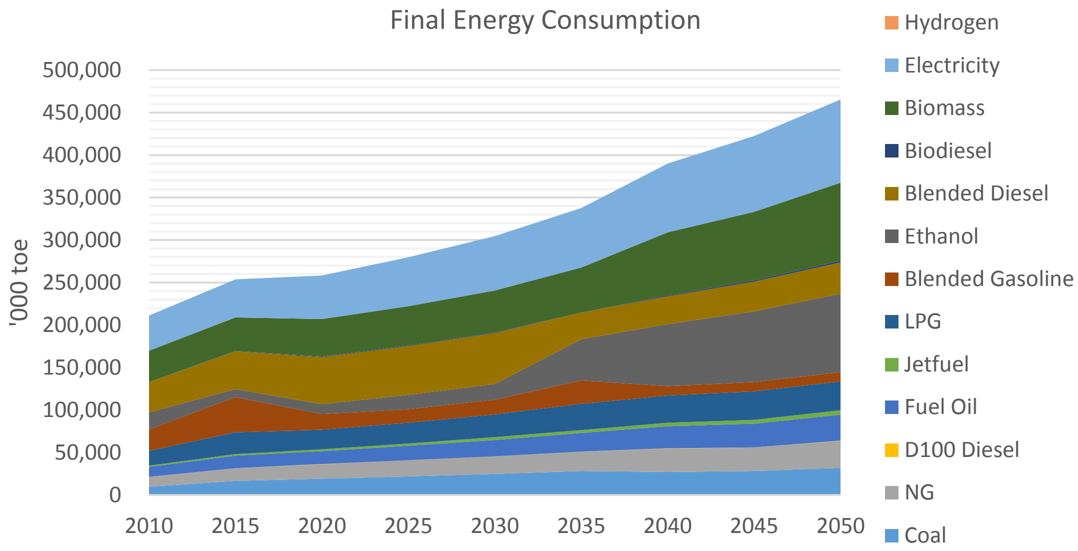

Figure A- 115 – Final Energy Consumption of scenario LC_DDRS_PFD – ktoe

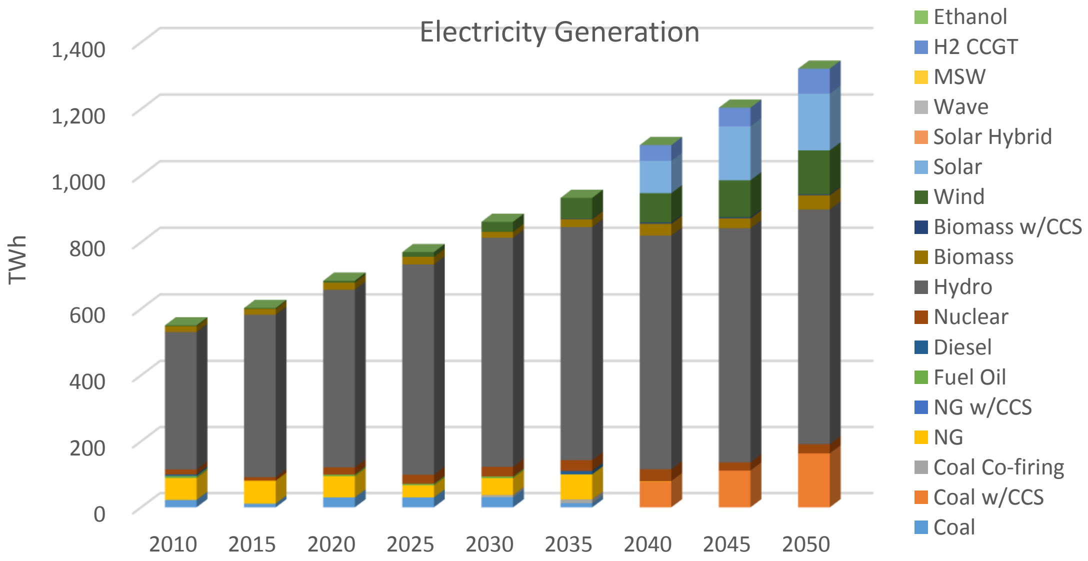

Figure A- 116 – Electricity Generation of scenario LC_DDRS_PFD – TWh

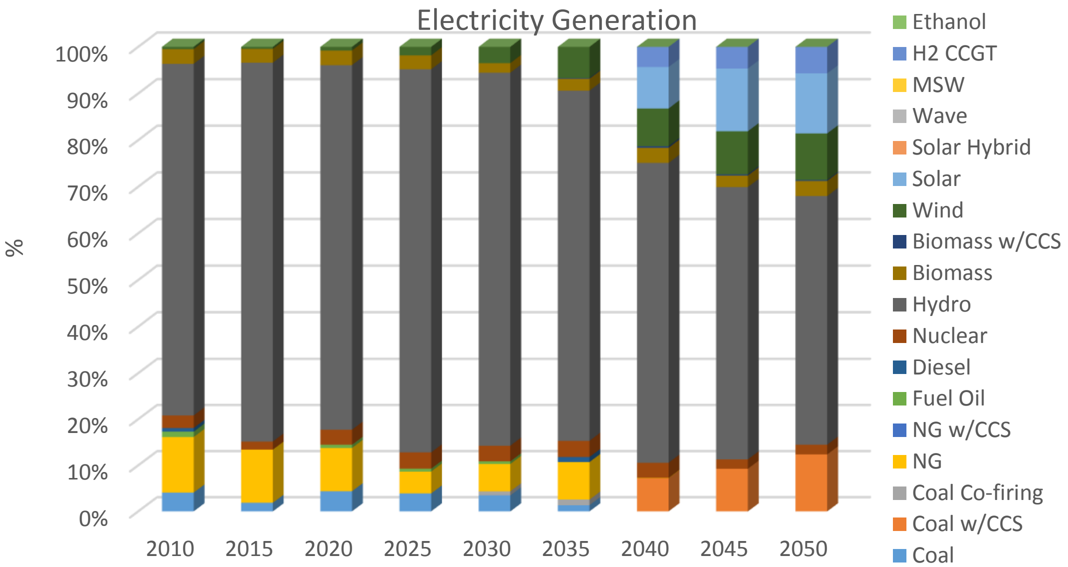

Figure A- 117 – Electricity Generation of scenario LC_DDRS_PFD – %

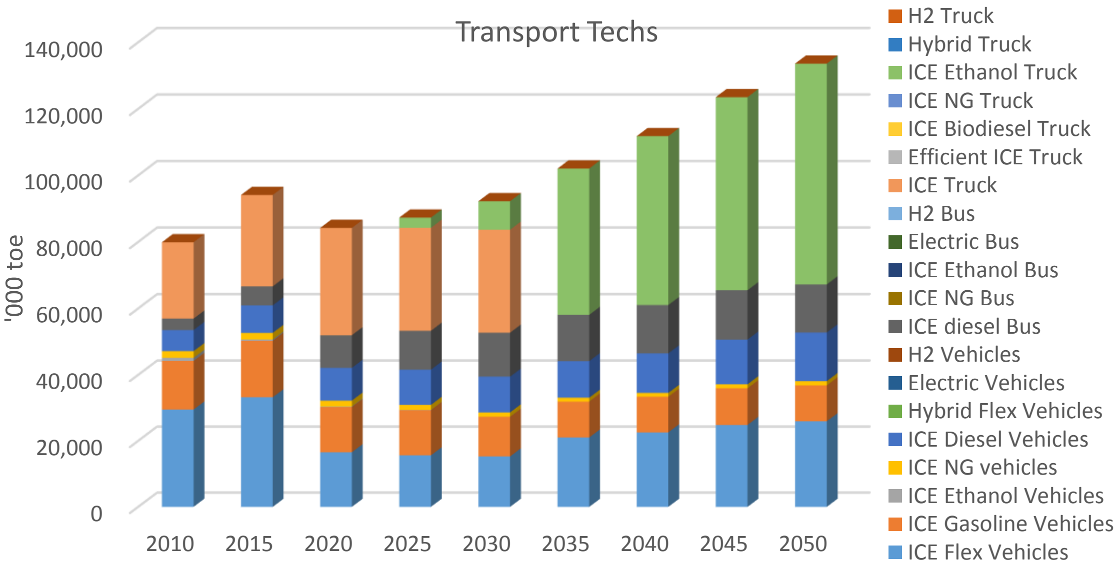

Figure A- 118 – Transport Sector Consumption of scenario LC_DDRS_PFD – ktoe

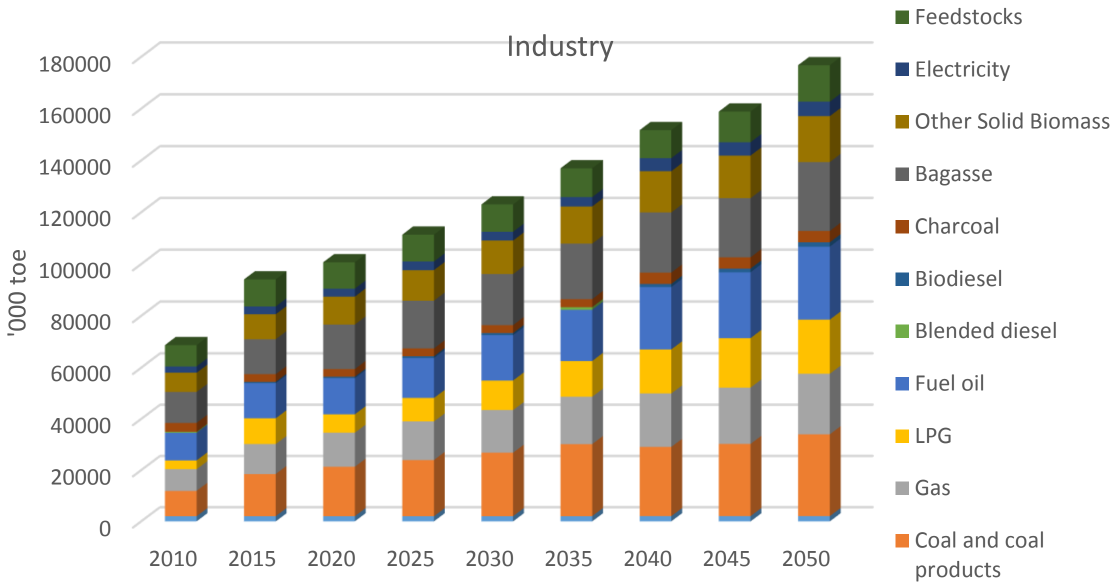

Figure A- 119 – Industry Consumption of scenario LC_DDRS_PFD – ktoe

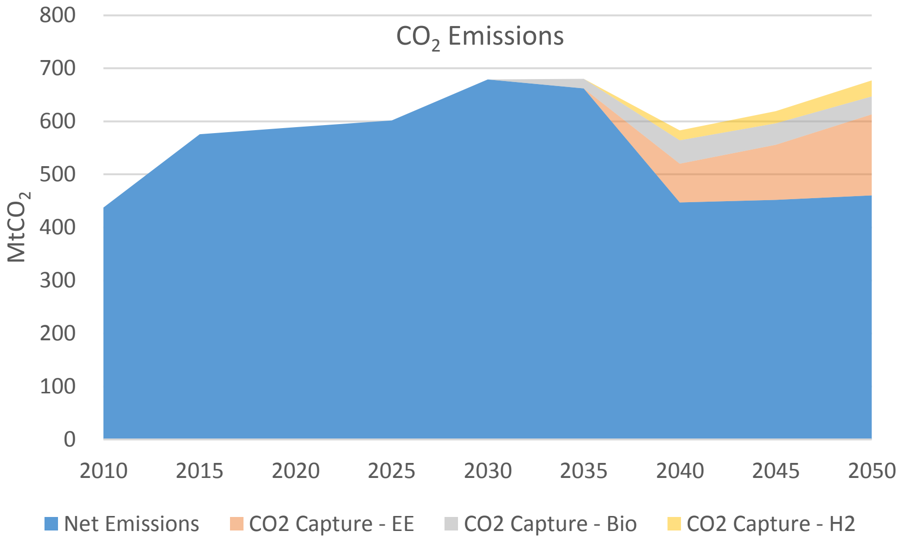

Figure A- 120 – CO$_2$ Emissions of scenario LC_DDRS_PFD – MtCO$_2$

Scenario LC_DDRS_MD

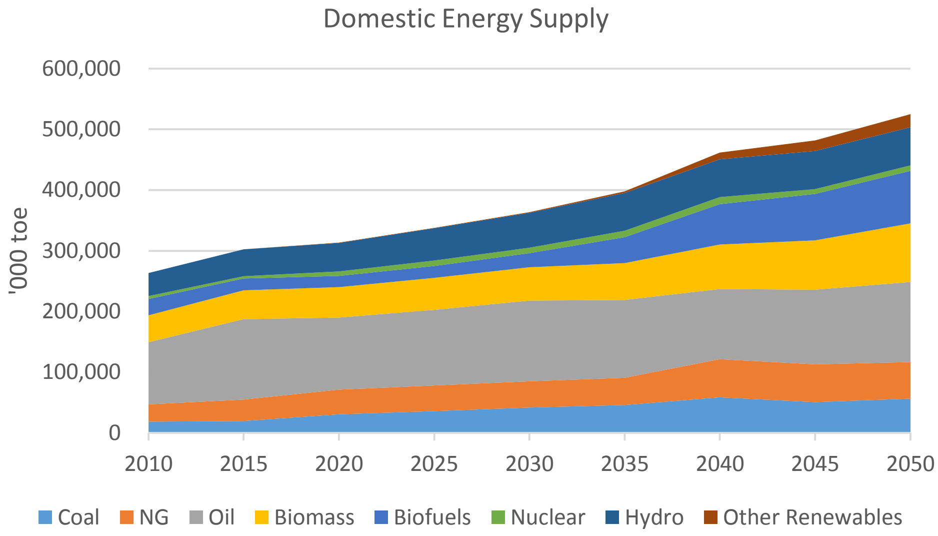

Figure A- 121 – Domestic Primary Energy Supply of scenario LC_DDRS_MD – ktoe

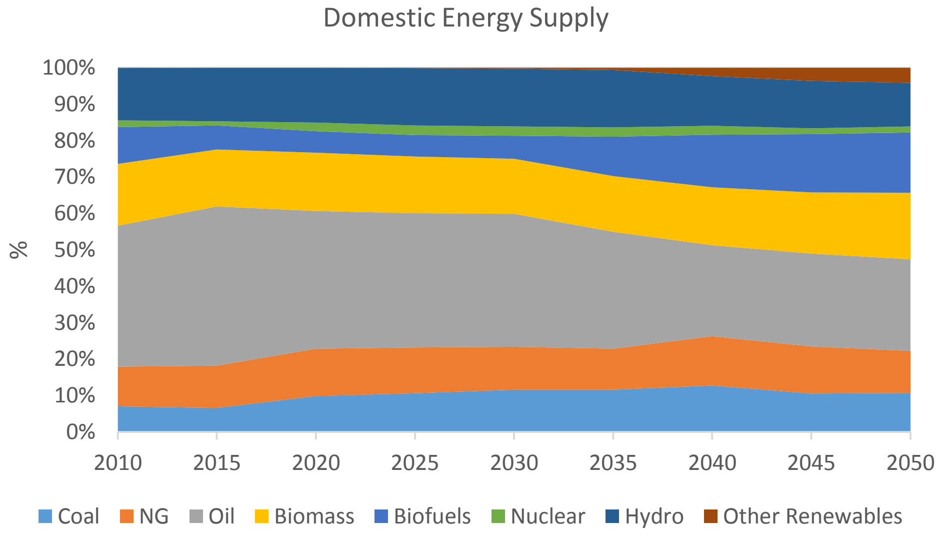

Figure A- 122 – Domestic Primary Energy Supply of scenario LC_DDRS_MD - %

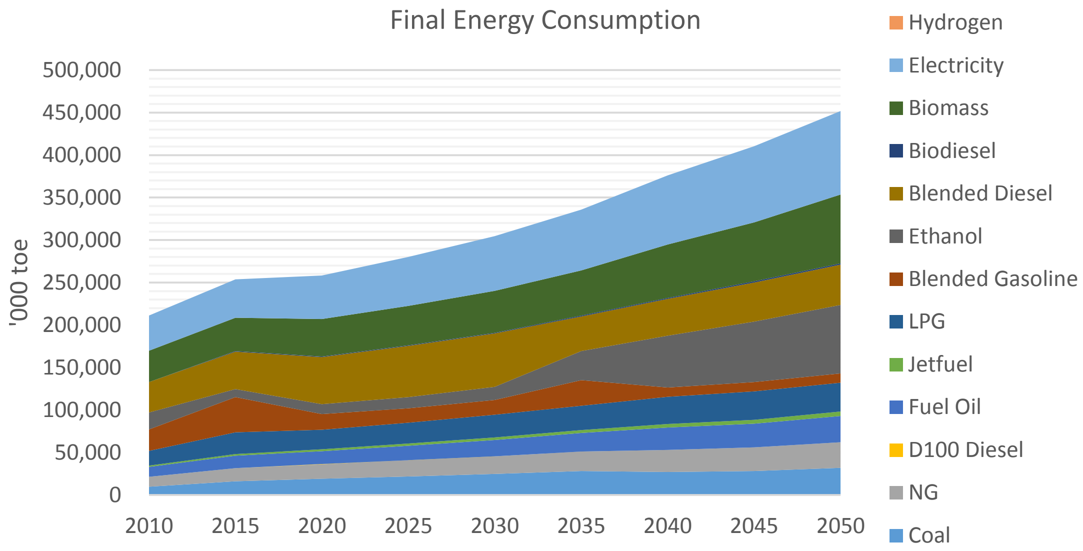

Figure A- 123 – Final Energy Consumption of scenario LC_DDRS_MD – ktoe

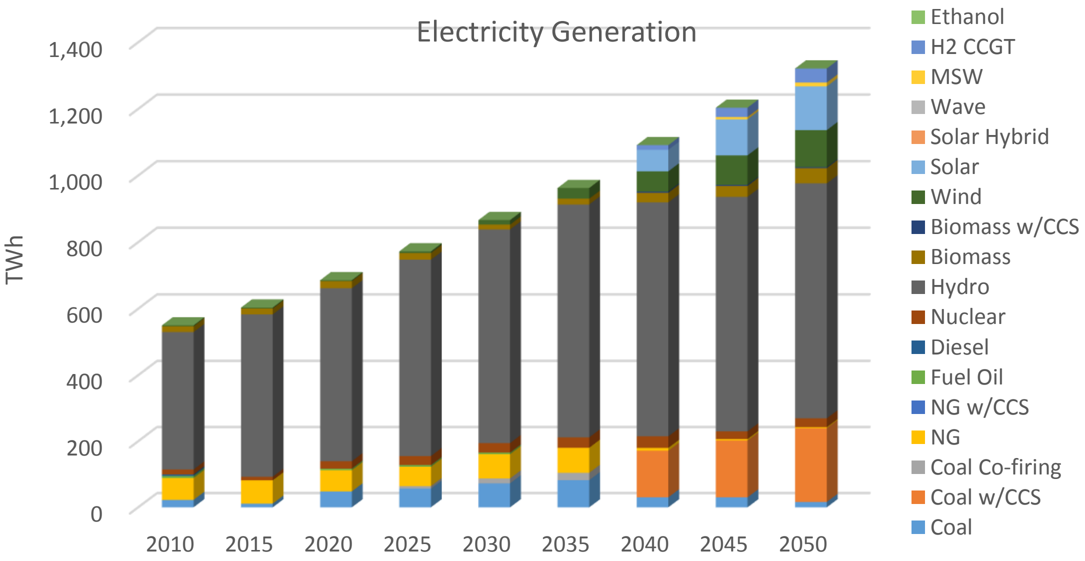

Figure A- 124 – Electricity Generation of scenario LC_DDRS_MD – TWh

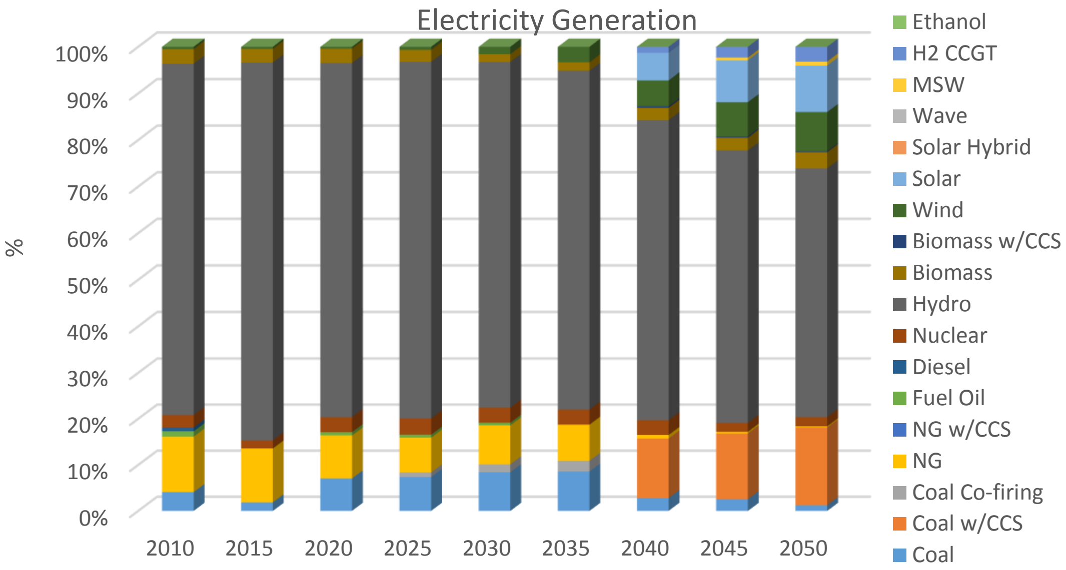

Figure A- 125 – Electricity Generation of scenario LC_DDRS_MD – %

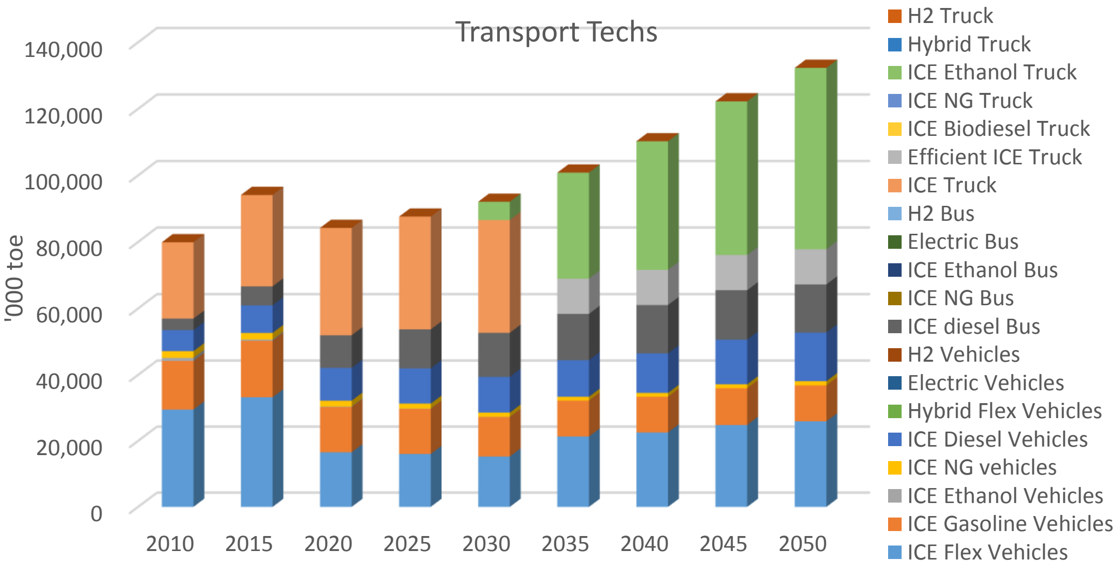

Figure A- 126 – Transport Sector Consumption of scenario LC_DDRS_MD – ktoe

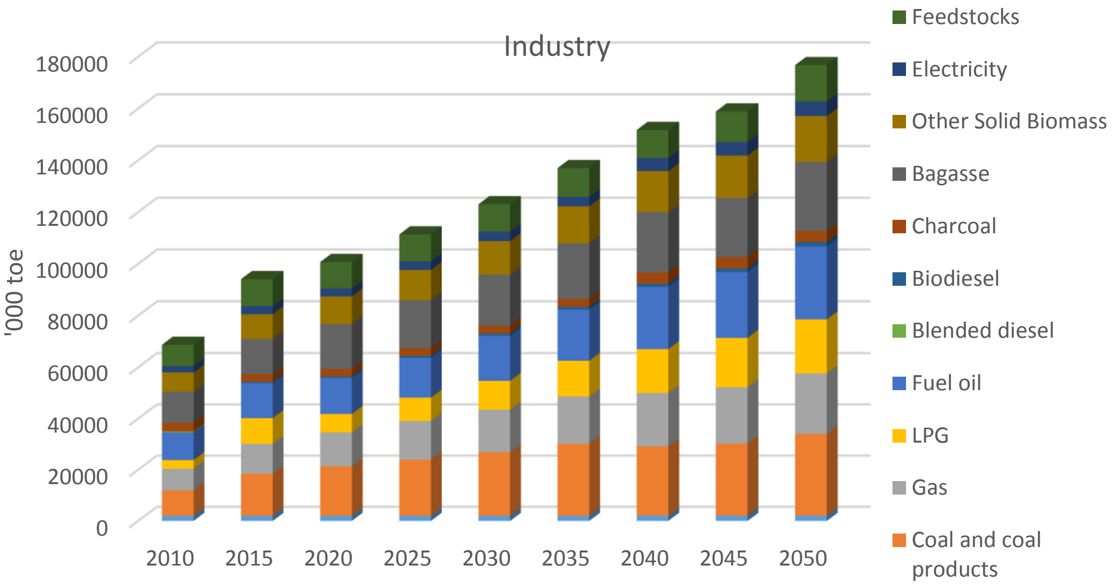

Figure A- 127 – Industry Consumption of scenario LC_DDRS_MD – ktoe

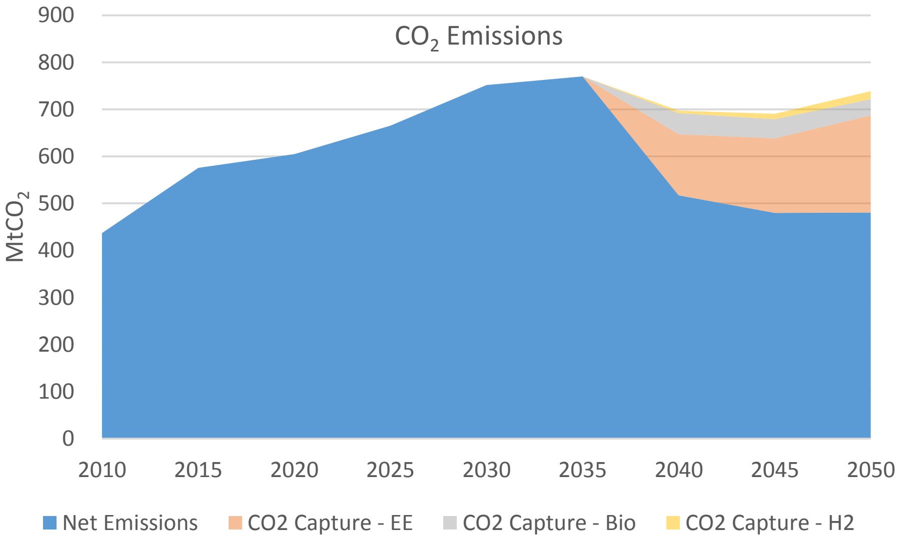

Figure A- 128 – CO_2 Emissions of scenario LC_DDRS_MD – $MtCO_2$