Universität Stuttgart
IER Institut für Energiewirtschaft
und Rationelle Energieanwendung

Forschungsbericht

Analysis of the relative roles of supply-side and demand-side measures in tackling global climate change – Application of a hybrid energy system model

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Mousavi

Band 139

Analysis of the relative roles of supply-side and demand-side measures in tackling global climate change –

Application of a hybrid energy system model

Von der Fakultät Energie-, Verfahrens- und Biotechnik der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

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Tag der Einreichung:	04. Juni 2018
Tag der mündlichen Prüfung:	29. Januar 2019

Institut für Energiewirtschaft und Rationelle Energieanwendung

Universität Stuttgart

2019

ISSN 0938-1228

D 93 (Dissertation der Universität Stuttgart)

Acknowledgements

Many people have contributed intellectually and spiritually to this work, and they deserve my sincere gratitude. First of all, I would like to express my deep sense of thanks and gratitude to my first supervisor, Prof. Dr.-Ing. Alfred Voss for his support and guidance throughout this work. His generosity and accommodation have helped to make this work possible. I would also like to thank my second supervisor. Prof. Dr. rer. Pol. Wolf Fichtner for supporting me to successfully conclude this dissertation.

PD. Dr.-Ing. Markus Blesl has been there to support me over the five years of my study. I would like to thank him. I also thank Prof. Dr.-Ing. Kai Hufendiek, the head of the IER institute, for giving me the opportunity to carry out this research at IER.

A very special gratitude to Dr. rer. pol. Ulrich Fahl. It was a pleasure to talk with him and hear his thoughts on various aspects of energy-economics.

I also want to thank Dr. Thomas Haas, Martin Spengler, Claudia Heydorn, Michael Wiesmeth, Lukasz Brodecki, Julia Welsch, Nikolai Klempp and all other colleagues at IER institute for their unforgettable help and encouragement.

I would like to thank the Helmholtz Research School on Energy Scenarios for funding the first three and half years of this research and providing me a structured educational programme in energy scenarios and modelling.

I would like also to take this opportunity to thank my parents for providing me with continuous encouragement throughout my years of study.

Finally, it is my privilege to express my very profound gratitude to my wife, whose understanding, patience and emotional support enabled me to carry out the dissertation.

Munich, December 2018

Babak Mousavi

Table of contents

List of figures

List of tables

List of abbreviations

AFR	Africa
AUS	Australia
AMS	American meteorological society
BECCS	Biomass with CCS
BIO	Bioenergy
BP	British Petroleum
BU	Bottom-up
Bv-Km	Billion Vehicle-Kilometers
CAN	Canada
CCS	Carbon Capture and Storage
CD	Cobb-Douglas
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
CHI	China
CHP	Combined Heat and Power
COP21	The 21th Conference of Parties
CSP	Concentrated Solar Power
DRI	Direct Reduced Iron
EEU	Eastern Europe
EEA	European Environment Agency
EFOM	Energy Flow Optimization Model
EJ	Exajoule
ETP	Energy Technology Perspectives
ETSAP	Energy Technology System Analysis Programme
EV	Electric Vehicle

FSU	Former Soviet Union
GDP	Gross Domestic Product
GDPP	Gross Domestic Product Per Capita
GWP	Gross World Product
HOU	Household
IEA	International Energy Agency
IER	Institute of Energy Economics and Rational Energy Use
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JPN	Japan
KLE	Capital-Labor-Energy
KLEM	Capital-Labor-Energy-Materials
Kt	Kiloton
LULUCF	Land-use, Land-use Change and Forestry
LP	Linear Programming
MARKAL	Market Allocation
MAC	Marginal Abatement Cost
MEA	Middle-East
MESSAGE	Model of Energy Supply Systems and the General Environmental Impact
MEX	Mexico
MRST	Marginal Rate of Technical Substitution
Mt	Megaton
NAP	The national Academies Press
NEMS	National Energy Modeling System
NEP	Nordic Energy Perspectives
NPV	Net Present Value

NUC	Nuclear
ODA	Other Developing Asia
OECD	Organization for Economic Cooperation and Development
PJ	Peta Joule
POP	Population
PV	Photovoltaic
PWh	Petawatt hour
QSF	Quadratic Supply-cost Function
RCP	Representative Concentration Pathway
RD&D	Research, Development and Demonstration
REN	Renewables
RES-E	Renewable Energy Supply of Electricity
RES	Reference Energy System
SKO	South Korea
TD	Top-down
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System
TIMES PanEU	Pan European TIMES model
TMSA	TIAM-MACRO Stand-Alone
TWh	Terawatt hour
UN	United Nations
USA	United States of America
USD	United States dollar
VES	Variable Elasticity of Substitution
VRE	Variable Renewable Electricity
WEU	Western Europe

List of formula symbols

a	Capital-labor constant in production function
$AESC$	Annual energy system cost in TIAM
amp	Not included annualized investment cost of existing capacities
b	service demand constant in production function
C	Annual consumption
DD	Integrated demand decoupling factor
ddf	demand decoupling factor
$dfact$	Utility discount factor
DM	annual Energy-service demand in the MACRO model
DT	Annual energy-service demand in the TIAM model
E	Energy
EC	Annual energy system cost in MACRO
EF	Efficiency parameter
i	Commodity index
INV	Annual investment cost in MACRO
K	Annual capital
$kpvs$	Share of capital in the value added aggregate
L	Annual Labor index
M	Composite constant in Cobb-Douglas production function
$NEX(nmr)$	Annual net export of numéraire good
nwt	Negishi weight
P	Undiscounted marginal price
pvf	Present value factor
pwt	Period-length multiplier weight
qa	Constant term in quadratic supply cost function

$\boldsymbol{qb}$	Coefficient of energy-service demand in quadratic supply cost function
$\boldsymbol{r}$	Region index
$\boldsymbol{t}$	Time period index
$\boldsymbol{w}$	Real wage rate (Marginal production of labor in efficiency terms)
$\boldsymbol{y}$	Income per person
$\boldsymbol{Y}$	Annual production
$\boldsymbol{A_{KL}}$	Pair capital-labor
$\boldsymbol{a}^*$	New capital-labor constant
$\boldsymbol{b}^*$	New energy-service demand constant
$\boldsymbol{DD}^*$	New integrated demand decoupling factor
$\boldsymbol{ddf}^*$	New demand decoupling factor
$\boldsymbol{P_{KL}}$	Price for the pair capital-labor
$\boldsymbol{P_{dm}}$	Price for energy-service demand
$\boldsymbol{\rho}$	Substitution constant
$\boldsymbol{\gamma}$	Integration constant
$\boldsymbol{\pi}$	The capital share in total production at the baseline point
$\boldsymbol{\sigma}$	Elasticity of substitution parameter

Abstract

Climate change is one of the most critical issues facing the world today. In 2015, the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) codified an ambitious long-term global target: holding the increase in the global average temperature well-below 2°C. It is recognized that this goal is a safe guardrail and will reduce negative impacts of climate change, significantly. As a result, policy instruments for achieving this target have become of central interest in the current climate change debate. To meet the target, the energy sector offers a wide range of technological options, namely, energy efficiency improvement, shifting from high carbon-intensive fossil fuels to less carbon-intensive alternatives (e.g. switching from coal to natural gas), and the enhanced use of renewables, nuclear, and Carbon Capture and Storage (CCS). On the other hand, additional investments in cleaner technologies will, ceteris paribus, result in a higher price of energy services and consequently reduce demand for energy-services which is considered as a mitigation measure. This dissertation aims at exploring, in a systematic manner, the required energy system transformations and the associated price-dependent energy-service demand reductions in order to hold the increase in global average temperature well-below 2°C above pre-industrial levels by 2100. For a more comprehensive assessment, it also evaluates the macroeconomic implications of the climate mitigation policy. The analysis is carried out using a hybrid model which is a combination of a bottom-up, technology-rich model, TIAM (TIMES Integrated Assessment Model) and a top-down, macroeconomic model, MACRO. One of the key parameters of the TIAM-MACRO model is elasticity of substitution denoting the ease of substituting energy-service demand with other production factors in the model (i.e. capital-labor) as their relative prices change. In the original model, this parameter holds a constant value for all regions over time. To provide more insight into the role of energy-service demand reductions, this study additionally assumes that the elasticity parameter varies across regions and over time. Furthermore, due to the uncertainties around the potential for mitigation technologies, a set of different scenarios with respect to the potentials are considered. The main findings of this study highlight the importance of early action in all energy sectors. In fact, the necessity of achieving carbon neutrality worldwide by around 2065 reflects that there would be almost no room for delay. Renewables are found to be the main mitigation measure. Furthermore, biomass with CCS is an essential option to compensate for residual emissions in sectors (e.g., transport) where direct mitigation is more challenging. It is also revealed that reducing price-induced energy-service demands can contribute more than 20% of the cumulative CO_2 reduction. While reaching the mitigation target comes with considerable negative macroeconomic impacts, energy-service demand reductions play an important role in offsetting the impacts.

Kurzfassung

Der Klimawandel ist ein zentrales Problem, mit dem sich die Welt heute konfrontiert sieht. Im Jahr 2015 wurde im Pariser Klimaabkommen unter der Klimarahmenkonvention der Vereinten Nationen (UNFCCC) ein ehrgeiziges, langfristiges und globales Ziel festgeschrieben: Den Anstieg der globalen Durchschnittstemperatur deutlich unter 2°C im Vergleich zum vorindustriellen Zeitalter zu halten. Es wird davon ausgegangen, dass dieses Ziel die negativen Auswirkungen des Klimawandels in noch tolerierbaren Grenzen hält. Um dieses Ziel zu erreichen, bietet der Energiesektor ein breites Spektrum an technologischen Maßnahmen: Die Verbesserung der Energieeffizienz, der Übergang von kohlenstoffreichen zu kohlenstoffärmeren fossilen Brennstoffen, sowie die verstärkte Nutzung von erneuerbaren Energien, Kernenergie und CO_2-Abscheidung und -Speicherung (CCS). Darüber hinaus werden Investitionen in saubere Technologien, ceteris paribus, zu einem höheren Preis für Energiedienstleistungen führen und somit deren Nachfrage verringern, was auch als Minderungsmaßnahme angesehen werden kann. Ziel dieser Dissertation ist es, systematisch die notwendigen Energiesystemtransformationspfade und die damit verbundenen preisabhängigen Nachfragereduktionen zu untersuchen, um den Anstieg der globalen Durchschnittstemperatur bis 2100 deutlich unter 2°C zu halten. Dabei werden im Rahmen der Analyse auch die makroökonomischen Auswirkungen der Klimaschutzmaßnahmen bewertet. Die Untersuchung erfolgt mit Hilfe eines Hybridmodells TIAM-MACRO. Einer der Schlüsselparameter des TIAM-MACRO-Modells ist die Substitutionselastizität, die die direkte Substitution der Energiedienstleistungsnachfrage durch andere Produktionsfaktoren (z. B. Kapital-Arbeit) bei Änderung ihrer relativen Preise ermöglicht. Im ursprünglichen Modell hat dieser Parameter einen über die Zeit konstanten Wert für alle Regionen. Analysen mit regional differenzierten und zeitvariablen Elastizitätsparametern sollen die Bedeutung von Energienachfragereaktionen für die Treibhausgasreduktion aufzeigen. Darüber hinaus werden die Unsicherheiten bezüglich der Potenziale verschiedener CO_2-Minderungstechnologien hinsichtlich ihrer Auswirkungen auf den CO_2-Minderungspfad untersucht. Die Ergebnisse der Arbeit zeigen die Notwendigkeit von schnellen Veränderungen in allen Bereichen des Energiesystems auf, um bis zum Jahr 2065 weltweit Netto-Null-CO_2-Emissionen zu erreichen. Erneuerbare Energien leisten dabei den größten Beitrag zur Reduktion der CO_2-Emissionen. Biomasse mit CCS ist eine wichtige Option, um Restemissionen in Sektoren in denen eine direkte Minderung schwierig ist, wie z. B. im Verkehr, zu kompensieren. Es zeigt sich weiterhin, dass eine Reduktion der Energienachfrage mit bis zu 20% zur Reduktion des kumulierten CO_2-Ausstoßes beitragen kann. Die Erreichung des globalen Minderungsziels ist insgesamt mit signifikanten negativen makroökonomischen Effekte verbunden, die durch Nachfragereaktionen, d.h. die Reduktion der Energiedienstleistungsnachfrage abgemildert werden.

1 Introduction

1.1 Climate change

Climate change is becoming an increasingly important issue that must be addressed by all nations. This issue is so dire that scientists and policymakers believe that it is among the most serious global concerns (Dessler, 2012). In recent years, climate change has taken center stage in the world political and scientific discussions. To discuss climate change and its major causes the term ‘climate’ should first be defined. The American Metrological Society defines it as:

“The slowly varying aspects of the atmosphere–hydrosphere–land surface system. It is typically characterized in terms of suitable averages of the climate system over periods of a month or more, taking into consideration the variability in time of these averaged quantities” (AMS, 2012a).

Thus, climate changes if its specifications differ from one period to another. Temperature, precipitation and sea-level are well-known specifications which are widely used to describe the climate system (The Royal Society, 2014). The American Metrological Society gives a more precise definition of the term ‘climate change’ as follow:

“Any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer” (AMS, 2012b).

Starting in the early 19th, based on many lines of evidence scientists recognized that Earth’s climate is changing. Figure 1-1 shows the average air temperature anomaly[1] of the Earth over the period 1880 to 2010 (relative to the average temperature of 1951-1980), which comes from widespread thermometer records. This graph shows that the global mean air temperature is increasing from each decade to the next. Thus, it reflects recent ‘global warming’ which refers to the long-term increase in average global atmospheric temperature.

Global warming has a number of negative impacts on the environment. Higher precipitations, retreating glaciers, rising seas, and shrinking lakes are some of these physical changes (Bodansky, 2001). However, such changes are only the beginning of the negative impacts of climate change. More strong and frequent floods, storms and droughts, increased erosion, and lower availability of fresh water are just some examples of the second-step adverse consequences of the climate change which consequently lead to catastrophic damages in natural and human systems. McMichael et al. (1997), in particular, discussed harmful effects of global warming on health and quality of life of humankind,

[1] A temperature anomaly is the difference between the actual temperature and a reference temperature (Dessler, 2012)

which have worried not only scientists but also the general public about the future of the climate system.

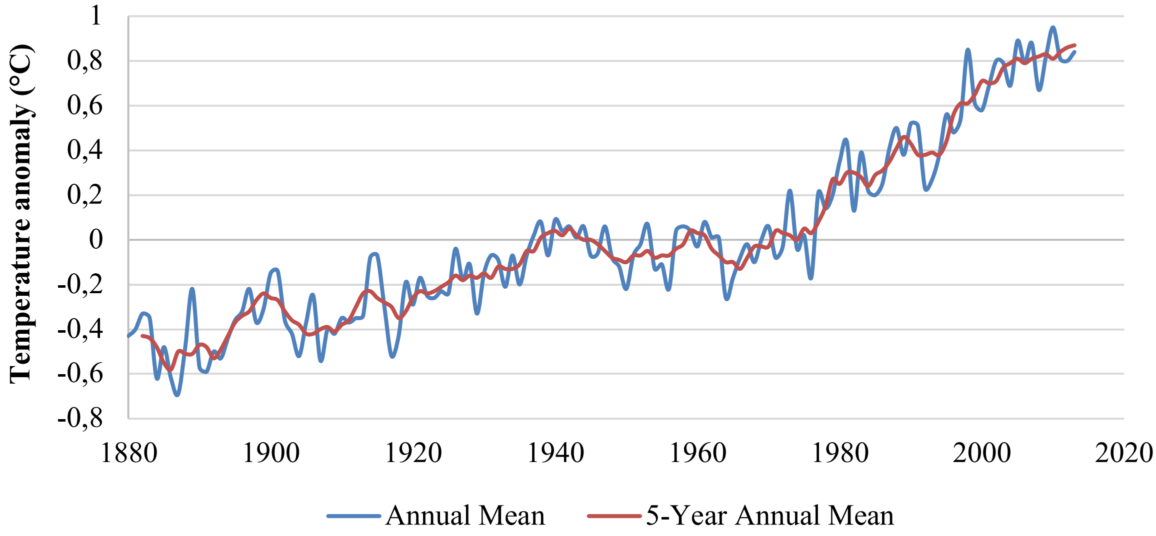


Figure 1-1: Global annual mean and 5-year annual mean air temperature anomalies relative 1951-1980 mean – Source: Hansen et al. (2017)

1.2 Causes of climate change

To identify the major cause of recent global warming, scientists examine different mechanisms that have influenced the climate system in the past. Physicists believe that natural variations (e.g., the sun's evolution) are some possible reasons for this phenomenon (Lean, 2000). However, such variations cannot sufficiently explain the rapid warming of the past few decades. Conversely, there is abundant evidence that recent warming is mainly caused by the increase in greenhouse gases in the atmosphere, which is due primarily to human activities (e.g., burning fossil fuels). In fact, a number of observations present a consistent, strong, almost linear relationship between cumulative greenhouse gases (mainly CO_2, CH_4, and N_2O) and the rise of global temperature change (IPCC, 2014a). Not only overwhelming evidence supports this hypothesis but there are also strong theoretical explanations for it, including some simple arguments (see e.g., Dessler, 2012) and complicated calculations of climate models.

In this regard, the International Panel on Climate Change (IPCC) in its 2007 report came to the following conclusion: "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC, 2007a; P.4). Although radiation modifying species other than CO_2 contribute to anthropogenic climate change, most of the scientific and political debates shed light on CO_2 emissions as the dominant factor (Myhre et al., 2013). This can be traced back to the fact that CO_2 emissions capture the vast majority of total GHG emissions. In 2014, for example, CO_2 emissions accounted for 76% of the totally emitted global greenhouse gases (see Figure 1-2). On the other hand, the majority of the CH_4, and N_2O (which are collectively referred to as Non-CO_2 gases) come from the agricultural sector (IPCC, 2007b) and therefore are not directly related to the energy sector. However, part of the CH_4 and N_2O emissions related to the energy sector, are emitted from the same source as CO_2 emissions. Therefore, cutting down CO_2 emissions leads to reduction of the other major greenhouse gases.

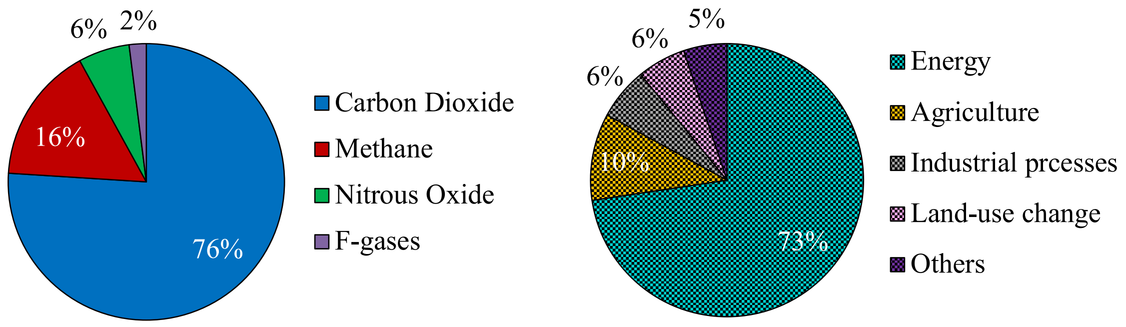


Figure 1-2: Global greenhouse gas emissions by gas (left) and by sector (right) in 2014 – Source: Climate Watch (2019)

According to IEA (2015), the annual global CO_2 emissions from fossil fuels have increased from almost 23.6 billion tons (Gt) in the 1990s to around 32.2 Gt in 2013. The historical evidence suggests that despite the steady cost reductions and rapid deployment of renewables, fossil fuels have remained the back-bone of the global energy system. This can also be traced back to their ease of use, huge availability of reservoirs, and structural dependency on fossil fuels of most of the current energy systems. Accordingly, although the level of emissions in the future and their negative impacts on the climate are uncertain, scientists are confident that without more ambitious climate policies than those in force today, the emissions from fossil fuel combustion will continue to grow notably. This leads to an average warming of at least 2.6 to 4.8 °C in addition to that which has already occurred today would be expected by the end of the 21^{st} century (The Royal Society, 2014). Figure 1-3 shows a prediction of the geographical pattern of surface warming over the 21^{st} century.

It is important to note that adverse consequences of climate change are not restricted to those of global warming. Ocean acidification is another major harmful impact of increasing CO_2 concentrations in the atmosphere leading to damages in marine ecosystems (Upton and Folger, 2013). Furthermore, real-world interactions between complex systems may cause them to exhibit new behaviors that cannot be clearly considered in the climate models (Schneider, 2004). Many scientists put stress on abrupt climate change as a tremendous and rapid consequence of continued adding of CO_2 to the atmosphere (see e.g. Rahmstorf 2002). The National Academy Press (NAP) broadly discussed potential abrupt changes in the climate system that might be caused by anthropogenic emissions

(NAP, 2013). Although the probability of an abrupt climate change is relatively low, due to its extremely large irreversible consequences it is imperative to be considered.

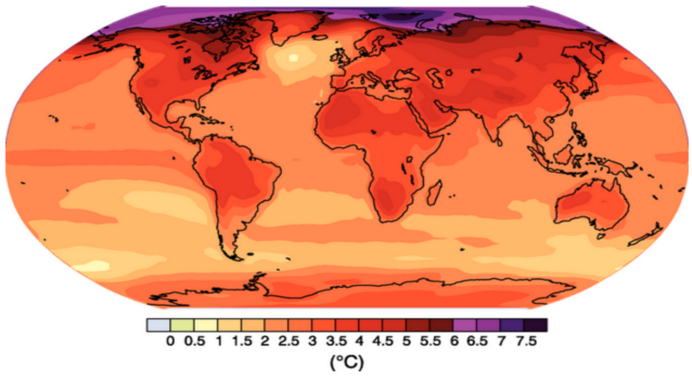


Figure 1-3: Projected surface temperature changes for the late 21st century (2090-2099), relative to the period 1980-1999 – Source: IPCC, (2007)

In a nutshell, increasing CO_2 emissions –mainly due to the combustion of fossil fuel– carries with it strong negative impacts on the climate system. Therefore, to reduce the negative consequences, it is crucial to curb the emissions in an effective manner.

1.3 Climate change mitigation

Generally speaking, adaptation, geo-engineering and mitigation are three recognized ways of attempting to cope with climate change. Figure 1-4 illustrates the cause and effect chain of climate change and three general measures to tackle climate change. Adaptation refers to a wide range of short-term activities (e.g., building seawalls in response to sea-level rise) that aim to moderate the harmful effects of climate change and to cope with unavoidable negative impacts of it (Chambwera and Stage, 2010). Since all climate changes are not reversible, adaptation will necessarily be required in the future. Nonetheless, relying on this option, as the only solution to climate change, is subject to moral and practical limitations (Chambwera and Stage, 2010; IPCC, 2008).

The second general option to address climate change is geo-engineering which can be defined as “the intentional, large-scale intervention in the Earth’s oceans, soils and/or the atmosphere with the aim of combatting climate change” (Bronson et al., 2009; P.5). In essence, it refers to manipulating the climate system in order to prevent it from changing. ‘Carbon cycle engineering’ and ‘solar radiation management’ are two dominant actions of this approach (Gordijn and Have, 2012). Although geo-engineering shifts some limitations of adaptation, it is likely to be an expensive and risky approach and may have some other serious negative environmental effects (IPCC, 1995; Robock, 2008).

The third attempt to tackle climate change is mitigation. In essence, mitigation refers to interventions and policies aimed to cutting emissions of greenhouse gases (especially CO_2) and thereby preventing the climate from changing (Chambwera and Stage, 2010).

Since it deals with the main driving force of climate change (i.e., emissions), it is considered to be the long-term key solution to address climate change and minimize its negative consequences in the future.

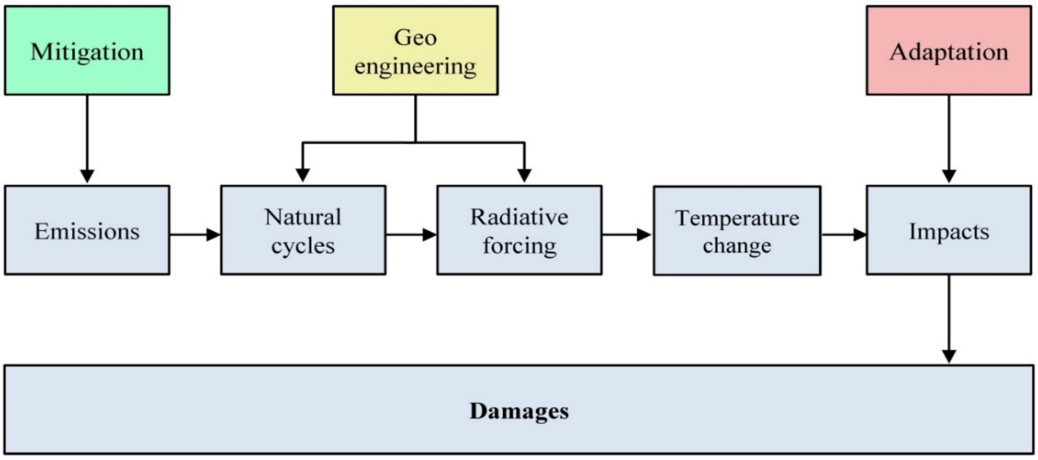


Figure 1-4: Cause-effect chain of climate change and alternative measures to limit it – Based on Bauer (2005).

To reduce or prevent emissions, a wide range of policy instruments will need to be deployed. Considering the fact that all nations are emitting greenhouse gases, effective actions to mitigate climate change should be taken based on international agreements. One of the easiest ways to set a long-term global climate target is to determine an upper limit for temperature increase. This limitation should be tight enough to prevent dangerous impacts of climate change. Due to the fact that climate impacts are not distributed evenly over the globe (Mahlstein et al., 2011) and the possibilities to cope with or adapt to the impacts vary among regions tremendously, there is no concrete scientific analysis that determines the most appropriate threshold. However, many scientific bodies believe that in order to avoid the most severe negative consequences, it is necessary to keep the total global average temperature increase below 2°C relative to pre-industrial levels (Hassol et al., 2006). The 21st Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) which was held in Paris in 2015, moved one step further and codified aspirations to hold the increase in the global average temperature to “well-below 2°C” above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. It is recognized that these ambitious targets are a safe guardrail and will reduce negative impacts of climate change, significantly. As a result, policy instruments for achieving the well-below 2°C and 1.5°C targets have become of central interest in the current climate change debate.

To limit total human-induced warming to less than 1.5°C, 2°C and 3°C relative to pre-industrial levels, there are attempts at estimating the additional allowable amount of CO_2 emissions, known as the ‘carbon budget’, consistent with the stated temperature limits at different levels of probability (Table 1-1). These probabilities reflect the considerable uncertainty around the sensitivity of global warming to CO_2 emissions. Although there is no commonly agreed definition of what exactly constitutes a well-below 2°C result (IEA, 2017), according to WEO (2016), this target can be interpreted to stay within the range of a reasonable chance of keeping global average temperature increase below 2°C and also a reasonable chance of achieving a 1.5°C consistent goal. IEA (2017), for instance, considered it as a 66% probability of achieving a 2°C target.

The table also presents the number of years remaining until we run out of the carbon budgets, assuming current rate of global emissions. For example, it shows that without more ambitious mitigation policies than those in force today, the threshold of staying below 2°C with a probability of at least 66% will be breached within 19 years.

Table 1-1: Carbon budgets consistent with limiting global warming to less than 1.5 °C, 2 °C and 3 °C limits at three different levels of probability – Based on IPCC (2014b) and IEA (2017)

	Temperature rise in degree (above pre-industrial)		
	<1.5 °C	**<2 °C**	**<3 °C**
For a 66% chance			
Carbon budget ($GtCO_2$) as of 1870	2250	2900	4200
Carbon budget ($GtCO_2$) as of 2017	162	762	2162
*Number of years remaining from 2017**	**4**	**19**	**54**
For a 50% chance			
Carbon budget ($GtCO_2$) as of 1870	2250	3000	4500
Carbon budget ($GtCO_2$) as of 2017	312	1062	2562
*Number of years remaining from 2017**	**8**	**27**	**64**
For a 33% chance			
Carbon budget ($GtCO_2$) as of 1970	2250	3300	4850
Carbon budget ($GtCO_2$) as of 2017	612	1262	3012
*Number of years remaining from 2017**	**15**	**32**	**75**

* Estimated from the budget remaining in 2017 divided by the overall emissions in 2017

1.4 CO_2 mitigation measures

To reduce CO_2 emissions to a desired level, there is no single mitigation option; instead, the energy sector offers a wide range of options that can be deployed. The mitigation measures can be divided into supply-side and demand-side measures. The supply-side measures are efficiency improvements in energy-supply technologies, shifting from carbon-intensive fossil fuels to less carbon-intensive alternatives (e.g., switching from coal to natural gas), as well as the enhanced use of renewables, nuclear, and Carbon

Capture and Storage (CCS[2]). The demand-side measures geared toward energy-service demand reductions and efficiency improvements in end-use technologies.

To utilize renewable energies a broad set of different technologies exist today. Solar, wind, hydro, bioenergy, geothermal, wave and tidal are the main renewables which produce near zero CO_2 emissions. Hence, substitution of conventional fossil fuel sources with renewables leads to a reduction of overall carbon emissions of an energy system. Due to their advantages, governments around the world are placing faith in renewable energies in energy and climate related strategies at the national level and at the global scale (Resch et al., 2008). In 2016, renewables provided around half of the global electricity generation growth. Therefore, for a comprehensive investigation of future mitigation pathways it is of crucial importance to consider the role that renewables can play.

Nuclear energy is another mature low-carbon source for electricity generation, which is used or planned to be used in more than 40 countries in the world (Gralla et al., 2016). Next to hydro power, by providing more than 10% of the global electricity generation mix, nuclear was the second largest low-carbon electricity generator in the year 2016 (IEA, 2017). Despite the concerns regarding nuclear energy (e.g., nuclear waste management), it can be seen as a source of base-load power generation in the context of climate change mitigation (Kopytko and Perkins, 2011).

Alongside other low-carbon technologies, CCS is another mitigation option. It refers to a family of technologies that capture produced CO_2 from fuel combustion or industrial processes, compress them for transportation and then store them underground at a safe storage site (e.g., depleted oil and gas fields) (IPCC, 2007a). CCS can be applied to biomass processing or combustion. Biomass CCS can lead not only to reduced CO_2 emissions, but a net removal of emissions from the atmosphere – or negative emissions (Zep, 2013).

Another option to reduce emissions is shifting from high carbon intensive fossil fuels to less carbon intensive alternatives. For instance, substitution of coal with natural gas can reduce about 40% of CO_2 emissions per unit of input fuel (EPA, 2015).

Energy efficiency improvements that reduce the amount of energy required to deliver a given product or provide a given service can lead to a reduction in CO_2 emissions (IAC report, 2008). From the energy system perspective, energy efficiency improvement can be divided into supply-side (for energy supplier technologies) and demand-side (for end-use technologies).

According to the definition given by Fell (2017; P.9), "energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states". These include lighting, cooking, space heating and water heating.

[2] Also called Carbon Capture and Sequestration

Reducing demand of energy services can, ceteris paribus, lead to lower energy consumption and consequently reduce emissions in the whole energy system. Therefore, although it has a different nature than the technological measures, energy service demand reduction can also be regarded as a mitigation option (Fujimori et al., 2014). There is a line of evidence that energy-service demands are often reduced as a response to higher energy prices (Jerison and Quah, 2006). To explain this from a macroeconomic perspective, consider that each commodity has substitutes – other goods that can be used in its place. As the relative prices rise, people buy less of that commodity and more of its substitutes. Therefore, if all other factors remain constant, higher energy prices induce firms and individuals to reduce their energy-service demands by substituting them with other production factors (e.g., labor, capital).

On the other hand, meeting long-term climate target will require a vast deployment of more energy-efficient and less carbon-intensive technologies which change energy prices and consequently affect demand of energy-services. Hence, in addition to investing in cleaner technologies, an economic system allows its production firms to react to higher energy prices, caused by the climate policy, through reducing their energy-service demands (van der Werf, 2008). Figure 1-5 depicts how a decarbonization policy results in reducing price-induced energy-service demands which can consequently lead to CO_2 emissions reduction.

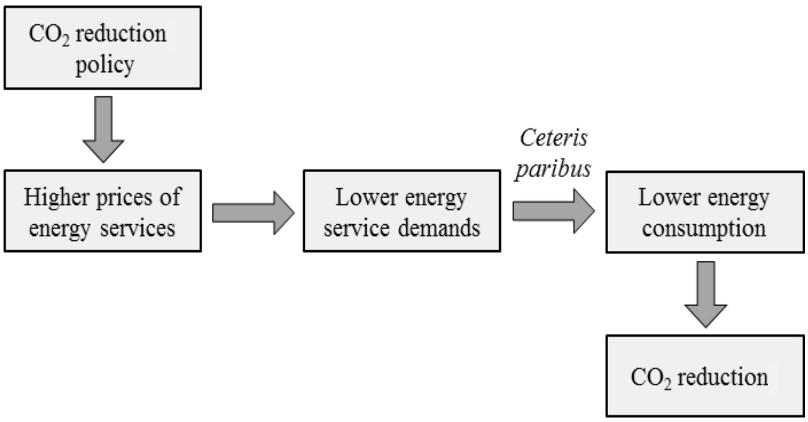


Figure 1-5: How price-induced energy service demand reductions can lead to reduction of CO_2 emissions

According to Webler and Tuler (2010), in addition to technological options, achieving decarbonization targets cost-effectively, may require reduction in energy-service demands. Besides, reducing energy-service demands may help an economy to deal with its sensitivity to energy price fluctuations (Koetse et al., 2008). Therefore, a comprehensive assessment of the mitigation pathways not only requires consideration of the contribution of all the discussed technological options, but needs to include the possible role that price-induced energy-service demand reductions will play.

1.5 Macroeconomic impacts of mitigation strategies

A question that policymakers and stakeholders often ask about mitigation strategies is ‘what are the impacts of those strategies on the whole economy?’ To answer this question, it is important to note that transitioning to a low-carbon economy requires significant reallocation of investments and resources of economic agents that may lead to structural changes in the economic system. Examples include higher investments in more energy efficient technologies, low- and zero-carbon technologies such as renewables, insulated buildings, and low-carbon transportation infrastructure. Due to the importance of the long-term economics of mitigating climate change, over the last decade, it has been extensively studied in several relevant reports on climate change, such as the IPCC's Fourth Assessment (IPCC, 2007) and the Stern review (Stern, 2007).

To study the impacts of a climate policy on the economic system appropriately, it is necessary to take into account both microeconomic and macroeconomic implications. While microeconomics is the study of the choices that individuals/businesses make, and the way these choices interact in the market, macroeconomics is the study of the performance of the whole economy at national to global scales (Parkin et al., 2005). Generally speaking, microeconomic costs can be divided into the associated costs of a specific technological mitigation measure and the total direct costs incurred in a specific energy sector (e.g., electricity). Such costs are computed using straightforward application of accounting and cost-engineering methodologies (Wei et al., 2012). One of the widely applied metrics to examine the microeconomic implications of mitigation actions is the marginal abatement cost (MAC) which represents the cost for one extra unit of CO_2 emissions eliminated via abatement options (IEA, 2017). Since MACs only refer to the marginal costs of reduced CO_2 emissions, they can be used to evaluate the cost-effectiveness of mitigation options.

However, impacts of mitigation strategies are not restricted to the direct microeconomic costs (IPCC, 2014b). Since energy is an important input factor of production, changing energy costs (caused by mitigation strategies) may influence the entire economy. Macroeconomic costs include the impacts that policy targeted toward the energy sector can have on economic decisions in the remaining sectors of the economy, as well as feedback in the energy sector, as the economy equilibrates to the new policy (Söderholm, 2012). For instance, firms facing a higher price of energy may either reduce their production or substitute away from energy input to other production inputs (e.g., capital and labor). Therefore, mitigation strategies may affect the level of gross domestic product (GDP) and its components which eventually influence human welfare (IPCC, 2014b). As stated by Walz and Schleich (2009), the analysis of macroeconomic effects of climate policies play a substantial role in shaping the political and scientific debate over climate mitigation strategies. Hence, ignoring impacts on and feedbacks from the rest of the economy can lead to biases in assessments of mitigation pathways.

Suffice to say that for a deep evaluation of future decarbonization strategies and consequently a better understanding of the relative contribution of the mitigation measures, it is vital to take into account not only microeconomic implications but also macroeconomic impacts of the strategies.

1.6 Main research objectives

This dissertation aims at exploring, in a systematic manner, the required global and regional energy system transformations to tackle global climate change, considering behavioral and technological interactions. To highlight large-scale forces, it quantifies the relative roles of technological measures and price-dependent energy-service demand reductions (Figure 1-6). To provide a deeper evaluation of future decarbonization strategies, it also takes into account the interconnections between the energy system and the rest of the economy to quantify the macroeconomic implications of the strategies. However, the dissertation does not take into account the macroeconomic implications of damages caused by climate change

Due to the uncertainties concerning the potential for low- and zero-carbon technologies, a set of different scenarios with respect to the assumed potentials of such technologies are defined. Furthermore, to reflect the key role of reducing demand for energy-services in meeting ambitious climate targets, additional scenarios concerning the possible contribution of this measure are given. Therefore, the dissertation turns toward the following tightly related research questions:

- What are the techno-economic characteristics of the long-term global and regional strategies toward an ambitious decarbonization goal?
- What contribution do the mitigation measures achieve to meet the decarbonization target up to the end of the century?
- How does increasing the potentials for low/zero carbon technologies influence decarbonization pathways, and what then is the robustness of otherwise techno-economically attractive portfolios and mitigation strategies?
- How critical is the role that energy-service demand reduction will play to meet the target in a more cost-effective manner?
- What are the macroeconomic impacts of the mitigation strategies?

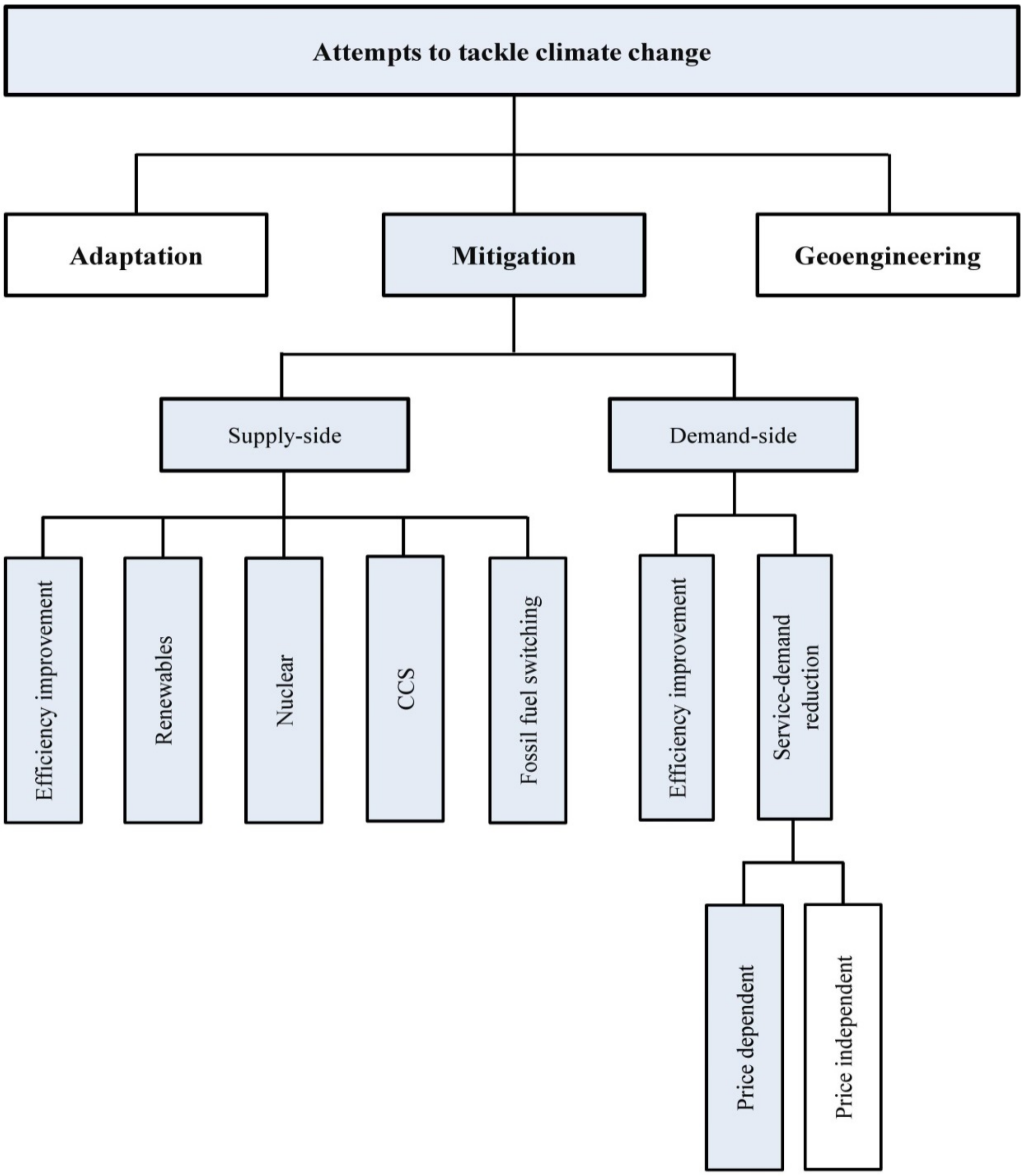


Figure 1-6: Attempts to tackle climate change with a specific focus on mitigation measures addressed in this dissertation

1.7 Structure of dissertation and methods

The analysis of this dissertation relies on a model-based energy scenario analysis and is centered at the global level which is crucially important in the context of climate change policies. To this end, a global multi-regional, technology-rich, bottom-up, partial equilibrium model, TIAM (TIMES Integrated Assessment Model) is applied. The model encompasses current and future energy technologies in a detailed manner and aims to find the least-cost mix of technologies to fulfill a given set of energy-service demands under different energy and climate related policies. Therefore, it is considered as an appropriate tool to study the role of technological measures. However, the model is not able to fully address the role of energy-service demands in combating climate change. Furthermore, since this model is restricted to the energy sector, it does not take into account the repercussions on the rest of the economy. To bridge these gaps, the TIAM model is linked to a top-down macroeconomic model, called MACRO.

One of the main parameters of the MACRO's production function is elasticity of substitution among the energy service demands and the non-energy inputs (i.e., capital-labor), which denotes the ease or difficulty of substituting the inputs as their relative prices change. In the original MACRO formulation, it is assumed that this parameter is constant over the planning time and across all regions. However, there is no evidence supporting this simplifying assumption. Therefore, this study develops a new production function with Variable Elasticity of Substitution (VES) which allows the elasticity of substitution to take a specific value for each region in each time period. A necessary condition to implement the VES approach is normalization of the production function. In addition, the normalization tackles the dimensionally inconsistency problem of the original MACRO's production function. Therefore, regardless of implementing the VES, it is necessary to normalize the production function of the MACRO model. The structure of the dissertation is summarized in Figure 1-7.

The rest of the dissertation is structured as follows: Chapter 2 reviews the literature on relative roles of mitigation measures. This chapter starts by giving a background on the CO_2 decomposition that has been extensively applied in this field. Then it turns to the studies that focused on historical evolution of CO_2 emissions and those that analyzed future mitigation pathways. This chapter concludes with a summary of the literature review.

In the third chapter a general picture of energy scenario analysis and a description of energy system modeling are presented. Subsequently, the TIMES model generator and its main features are given. In particular, this chapter presents the overall structure of the TIAM model which is a global incarnation of the TIMES model generator. Finally, to highlights the strengths of the TIAM model, a review of its applications in peer-reviewed journal articles is provided.

Chapter 4 starts by giving a general background on so called hybrid energy modeling approach and describes the advantages of applying hybrid energy models in the context of climate change mitigation. Subsequently, the overall structure of the MACRO model and a review of its applications are presented. Finally, this chapter elaborates the approach of linking TIAM with MACRO, followed by the main equations of the linkage and the required steps to implement the TIAM-MACRO model.

Two major methodological contributions of the dissertation, namely implementation of the VES production function and normalization of the production function are discussed in Chapter 5. It includes a detailed review of empirical observations of the VES in the context of capital and labor substitution, confirming that the VES is a more realistic production function than the Constant Elasticity of Substitution (CES) and Cobb-Douglas (CD) production forms. Moreover, the required changes to generalize the MACRO's production function to a VES function are discussed. Accordingly, a general background on normalization of production functions is presented. Finally, this chapter explains how the MACRO's production function is normalized to support the VES approach, followed by the other necessary changes in the model to adapt the new normalized VES production function.

In chapter 6, a set of scenarios for a comparative analysis of future global mitigation pathways is defined. It starts by outlining the main scenario assumptions and the characteristics of the employed scenarios. Subsequently, scenario results are presented and the required energy system transformations and the associated energy-service demands reduction in order to combat global climate change are discussed. Furthermore, the macroeconomic implications of the given decarbonization scenarios are presented.

The last chapter summarizes the dissertation and provides conclusions and outlook.

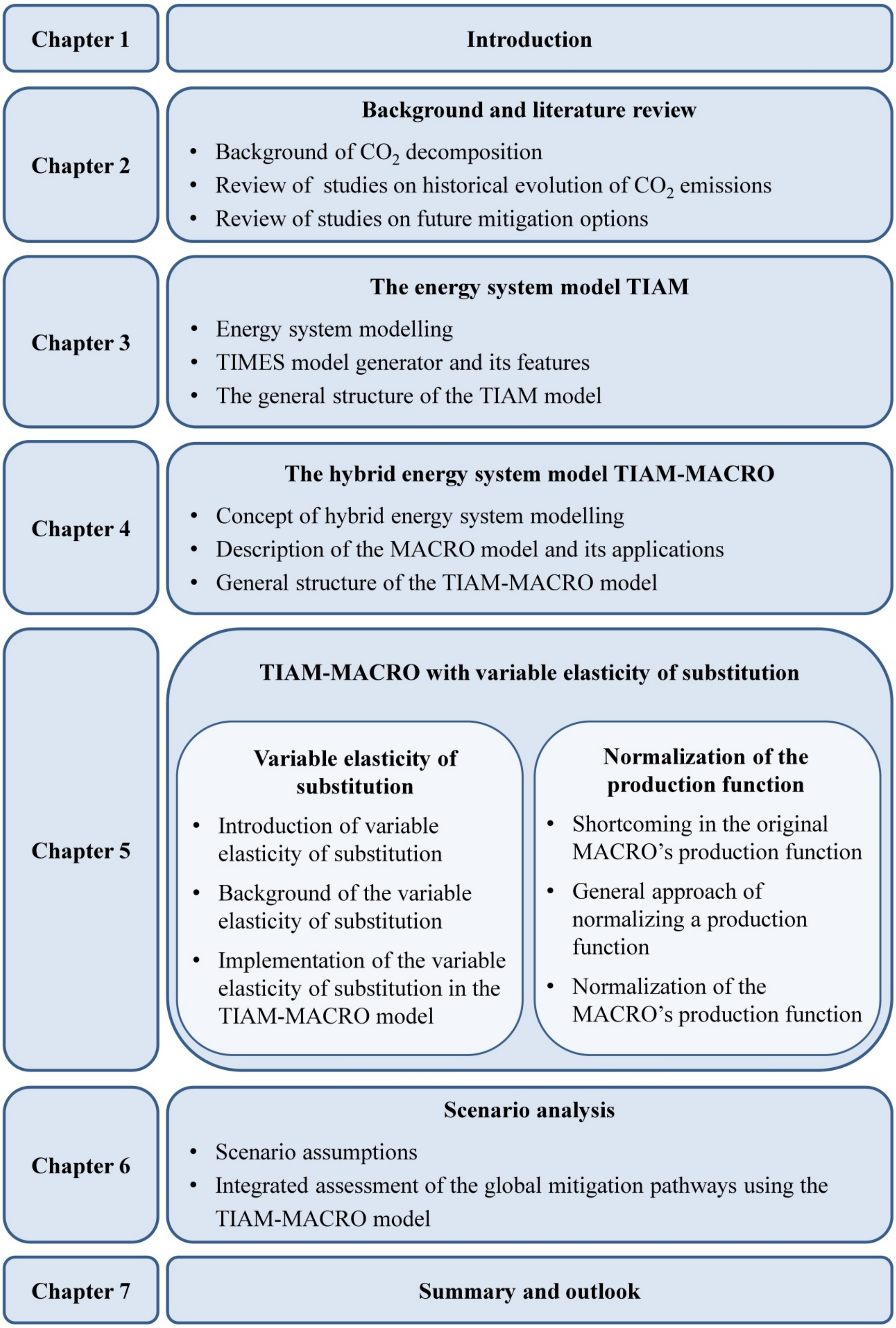


Figure 1-7: The structure of the dissertation

2 Relative roles of mitigation options: background and literature review

This chapter gives an overview of the existing studies in the literature that have dealt with the analysis of driving forces of historical emissions and investigation of the relative roles of mitigation measures in reducing long-term emissions. It starts by providing background on the CO_2 composition analysis which has been extensively used in this context. Subsequently, it turns to a brief review of studies focusing on historical evaluation of CO_2 emissions to analyze their main driving forces. These studies are classified according to the spatial coverage from national and regional to global studies. In a further section, a review of studies that have looked at the role of mitigation measures in meeting future decarbonization targets is given. These studies are categorized according to their modelling approach. Finally, the chapter is concluded by presenting research gaps in the existing literature on analysis of the relative roles of mitigation measures in tackling long-term climate targets.

2.1 Background of CO_2 decomposition

As carbon dioxide emissions and the associated negative impacts on the climate have gradually changed from a purely environmental issue to a serious global concern, the number of published studies in this context has risen tremendously. The vast majority of existing studies have aimed to identify and analyze the main driving forces of energy-related CO_2 emissions in order to detail required measures to combat climate change in a long-term perspective (Fisher et al., 2007). The studies can initially be classified according to their focus on (a) historical evolution of CO_2 emissions, (b) future decarbonization pathways.

In order to identify and measure the driving forces behind energy-related CO_2 emissions, a method that has been frequently used is 'decomposition analysis' (Ang and Zhang, 2000). In essence, decomposition analysis refers to separating an aggregated identity, usually either energy use or CO_2 emission, into its components (Akbostanci et al., 2011). In the early 1970s the focus of decomposition analysis moved from energy consumption toward greenhouse gas emissions by introducing the so-called 'IPAT identity' (Chertow, 2000). This identity is an easily understandable framework for evaluating the key human-driven forces behind environmental impact, such as air pollution. In essence, it presents that human environmental impact (I) is derived from population (P), affluence (A), and technology (T) (Eq. 2-1). Thus, the IPAT identity recasts the problem of reducing human environmental impact into the problem of reducing one or more of the influencing factors.

$$I = P \times A \times T \qquad \text{Eq. 2-1}$$

About 20 years later, Yoichi Kaya (Kaya, 1990) extended the IPAT framework by splitting the technology term into energy intensity and carbon intensity factors in order to look more deeply into driving forces of CO_2 emissions (Eq. 2-2). Despite its limitations (see e.g., Hwang

2013), the KAYA identity has been widely adopted by several studies including those of well-known institutions such as the International Energy Agency (IEA) (IEA, 2016a) and the International Panel on Climate Change (IPCC) (IPCC, 2014b). This is mainly due to its comprehensive and simple structure.

$$CO_2 = POP \times (\frac{GDP}{POP}) \times (\frac{E}{GDP}) \times (\frac{CO_2}{E}) \quad \text{Eq. 2-2}$$

Where:

CO_2	energy-related CO_2 emissions
POP	population
GDP	economic output
E	energy consumption

Besides population and affluence (GDP/POP), this approach takes into consideration energy intensity of economy (E/GDP), and carbon intensity of energy use (C/E) as influencing factors on energy-related CO_2 emissions. The former two factors influence CO_2 emissions via changing the energy demand (Shahbaz et al., 2015). Although in some countries such as China population control policies are in force (see e.g., Choukhmane et al. 2013), changing the size of the population in many countries may conflict with religious, social, political and cultural issues. Hence, efforts to tackle climate change by reducing population are politically unachievable and it cannot be seen as a mitigation option (Dessler, 2012). In addition, some recent studies (e.g., Riahi et al., 2007) pointed out that impact of population size on emissions may be offset by changes in other dependent drivers, thus leading to no dramatic changes in CO_2 emissions.

On the other hand, the latter two factors represent technology-related key drivers. The energy intensity reflects the structural, technological, and energy consumption characteristics of the economy (Williams et al., 2001). All else unchanged, declining energy intensity leads to CO_2 emissions reduction. Moreover, diminishing carbon intensity of energy consumption can decrease the overall CO_2 emissions. It can be concluded that the KAYA identity is a useful CO_2 decomposition method addressing both demand-side and supply-side factors that influence CO_2 emissions. However, as the explored driving forces in the KAYA are too aggregated, this identity is not able to provide a sufficient insight into drivers of emissions or the required mitigation measures to reduce them. As a result, recently this identity has served as a good basis for development of highly detailed decomposition identities containing more disaggregated and specific factors. Mahony (2013), for instance, proposed a developed KAYA identity to explicitly take into consideration the effect of low- and zero-carbon technologies (e.g., renewables).

The next section provides a brief overview of studies aiming to find major drivers of historical CO_2 emissions, which are mostly based on the KAYA identity. The literature in this context entails national, regional and global focuses. Therefore, to have a more structured perspective, the reviewed studies are classified according to the regional coverage.

2.2 Review of studies on historical evolution of CO_2 emissions

Although the focus of the dissertation is the relative roles of mitigation measures in combating future climate change, this section provides examples of studies that addressed forcing drivers of historical CO_2 emissions. The rationale is that analysis of changes in historical CO_2 emissions of a region/nation can facilitate the effective planning of future mitigation strategies for that region/nation. In addition, it may also provide important insights into the development mitigation pathways for other regions/nations (Mahony, 2013).

2.2.1 Studies at the country level

China has experienced a substantial increase in energy consumption and CO_2 emissions (Zhang et al., 2016). As shown in Figure 2-1, in 2016, China's CO_2 emissions from fossil fuels reached an all-time high of about 9.1 Gt of CO_2, putting the country as the top CO_2 emitter worldwide. Therefore, analysis of the factors that drive the growth of Chinese emissions is crucial to deal with climate change in an effective manner. Hence, for a deep and comprehensive investigation of the required mitigation measures to tackle climate change, it is of great importance to specifically focus on this country.

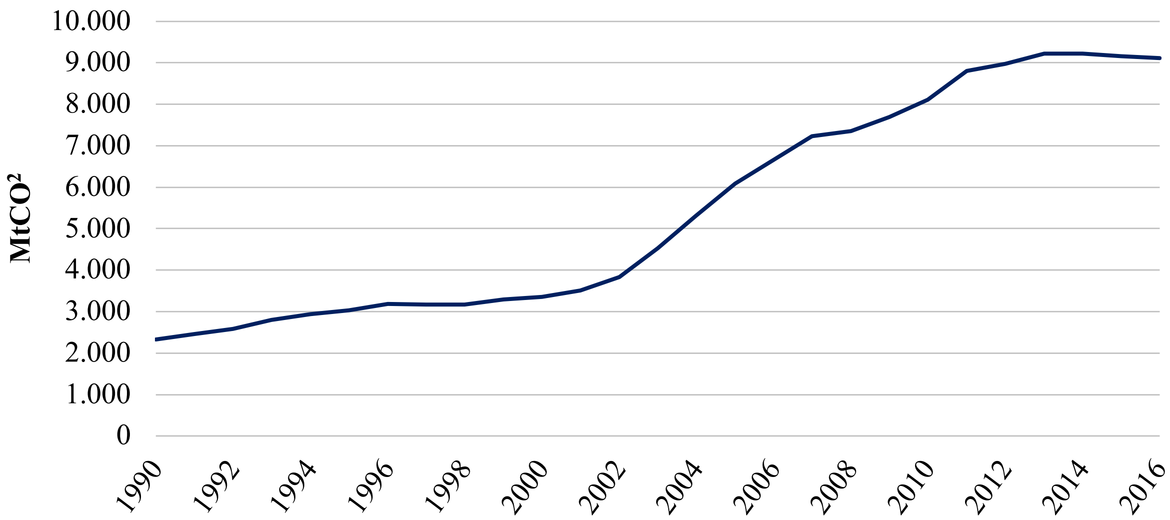


Figure 2-1: China CO_2 emissions from fuel consumption over the period 1990-2016 – Source: British Petroleum (2017)

It is not surprising that several studies have identified the major driving forces of Chinese CO_2 emissions. Examples include Zhang, (2000), Wang et al. (2005), Wu et al. (2006), Zhang et al. (2009), and Gao et al. (2016). The major findings of these studies show that improving energy intensity has made a considerable contribution in offsetting the Chinese CO_2 emissions growth.

However, there are a number of studies that have addressed the driving forces of CO_2 emissions in other countries. Some examples are: Cansino et al. (2015) examining the main drivers of Spain's CO_2 emissions in the period of 1995 to 2009, as well as Mousavi et al. (2017) quantifying the drivers of CO_2 emissions in Iran over 2003-2014. According to these studies, for both developed and developing countries, a suitable mitigation policy will need to significantly reduce energy intensity and increase renewables. In addition, some studies included behavioral aspects in the analysis of past trend of CO_2 emissions. For instance, Sumabat et al. (2016) studying driving forces of the CO_2 emissions from Philippines' electricity sector in the period 1991-2014, shed light on the significant role of lifestyle change of the population in reducing CO_2 emissions of this country.

2.2.2 Studies at the regional level

A vast body of the literature has extended the focus to analysis of historical emissions at the international scale. Lee and Oh (2006), for instance, concluded that fossil fuel switching in combination with energy efficiency improvement dampened increase in CO_2 emissions in Asia Pacific Economic Cooperation countries between 1980 and 1998. Karmellos et al. (2016) developing a decomposition approach, investigated the changes in CO_2 emissions from electricity generation across the countries in Europe, over the period 2000-2012. Level of activity, electricity intensity, electricity trade, efficiency of electricity generation and fuel mix were considered as the five leading driving forces of the emissions. Further, Kaivo-oja et al. (2014) investigated factors that influence the energy-related CO_2 emissions in three major economies in the world, namely China, United States and the EU-27 over the period 1960-2010, using a mathematical decomposition analysis. The results of this study present the existence of convergence regarding intensity effect toward CO_2 emissions reduction in contrast to divergences of structural effects between the regions. On the other hand, Lima et al. (2016) provided a cross-country assessment of the main energy-related CO_2 emission's drivers for Portugal, United Kingdom, Brazil and China from 1990 to 2010. They concluded that energy intensity and renewables have been the major drivers of changes in energy-related CO_2 emissions for the given regions. Andreoni and Galmarini (2016) extended the analysis to CO_2 emissions of 33 world countries from 1995 to 2007. Enhancing energy efficiency has been considered as the main element contributing to reduce the overall CO_2 emissions in all the countries. Furthermore, Sanchez and Stern (2016) discussed the relationship between both industrial and non-industrial (e.g., agricultural) greenhouse gas emissions, economic growth and other potential drivers of 129 nations over the period of 1971 to 2010. Major findings of this study reflect that economic growth is the key driver of aggregate emissions.

2.2.3 Studies at the global level

Although analysis of emissions at national and regional levels facilitates the development of mitigation strategies, the "global commons" characteristics described by Hardin (1968) imply that an appropriate assessment of the climate change problem has to be conducted at the global scale. The most comprehensive studies in this regard were conducted by International Panel on Climate Change (IPCC) and International Energy Agency (IEA). IPCC (2014) using the KAYA identity, analyzed the key influencing factors of total annual energy-related CO_2 emissions in four decades over the period 1971-2010. As depicted in Figure 2-2, GDP per Capita is found to be the main driver of recent change in global CO_2 emissions.

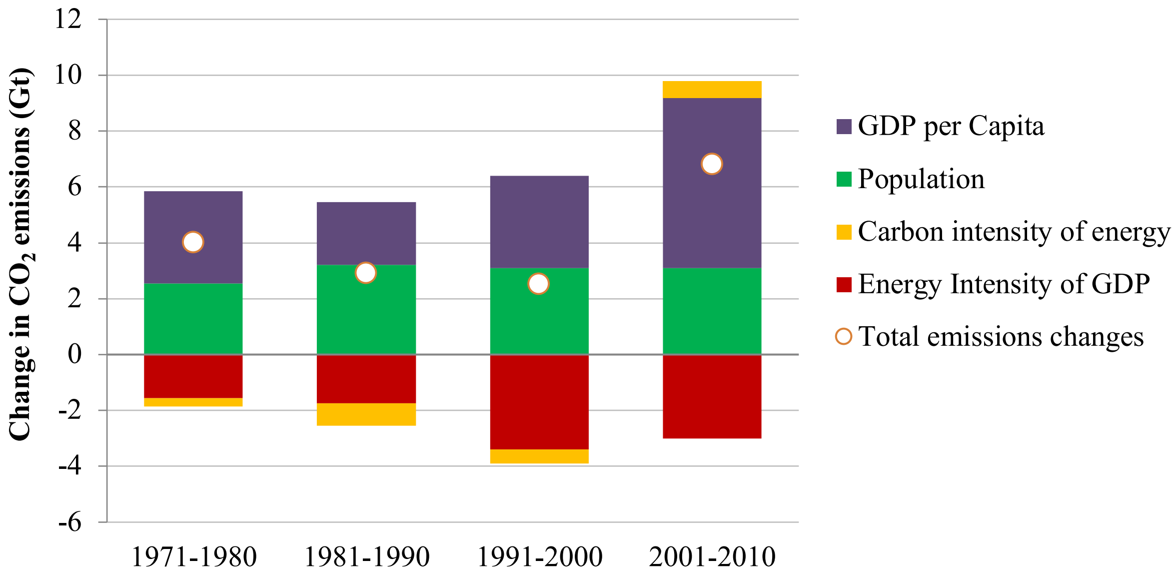


Figure 2-2: Decomposition of the changes in total global annual CO_2 emissions from fossil fuel combustion by decades, using KAYA identity – Source: IPCC (2014)

Using a similar approach, IEA (2016) investigated emissions from national to global levels. As illustrated in the Table 2-1, GDP per capita has been the leading driving force of CO_2 emissions across the globe over 1990-2014. In contrast, decreasing energy intensity has dampened the growth of emissions in this period.

On the other hand, there are some studies that have examined other aspects of global CO_2 emissions. Jiang and Guan (2016), for instance, investigated CO_2 emissions growth by fossil fuel type (coal, natural gas, oil), country group (developed or developing), demand type (consumption or investment), and industry group from 1995 to 2009. Findings of this study highlights that developed and developing countries have very different performances in terms of changes by fuel type and demand type. However, the growth in final demands has led to noticeable CO_2 growth worldwide.

Despite the aforementioned advantages, analysis of historical evolution of CO_2 emissions and their driving forces cannot adequately tackle future climate change in an efficient and effective manner. Primarily this is due to two reasons: first, as several nations have not yet implemented any CO_2 reduction policy, their behavior may change in the future when such policies are implemented. Second, such studies are not able to cover most of the innovative mitigation technologies (e.g., CCS) because they have not yet been commercialized. As expressed

by Zhang et al. (2014), a key measure for achieving ambitious mitigation targets effectively is the large-scale deployment of innovative technologies which will be induced by climate policies in the future. Therefore, an in-depth and integrated investigation of future mitigation strategies requires energy system models which enable us to capture not only the existing options, but also future innovative mitigation measures.

Table 2-1: Global CO_2 emissions and drivers - Kaya decomposition (1990=100) – Source: IEA (2016a)

	1990	1995	2000	2005	2010	2013	2014	% change (1990-2014)
CO_2 emissions	100	104	113	132	149	157	158	58%
Population	100	108	116	123	131	136	137	37%
GDP PPP per capita	100	103	115	131	148	158	162	62%
energy intensity	100	94	86	82	76	72	70	-30%
Carbon intensity	100	99	99	100	101	101	101	1%

Despite the aforementioned advantages, analysis of historical evolution of CO_2 emissions and their driving forces cannot adequately tackle future climate change in an efficient and effective manner. Primarily this is due to two reasons: first, as several nations have not yet implemented any CO_2 reduction policy, their behavior may change in the future when such policies are implemented. Second, such studies are not able to cover most of the innovative mitigation technologies (e.g., CCS) because they have not yet been commercialized. As expressed by Zhang et al. (2014), a key measure for achieving ambitious mitigation targets effectively is the large-scale deployment of innovative technologies which will be induced by climate policies in the future. Therefore, an in-depth and integrated investigation of future mitigation strategies requires energy system models which enable us to capture not only the existing options, but also future innovative mitigation measures.

2.3 Review of studies on future mitigation options

There is a vast literature analyzing the required energy transformations for meeting future climate mitigation targets. The studies in this context have employed different methodologies. Although, some studies rely on qualitative and expert assessment approaches (e.g., Pacala and Socolow, 2004; Dietz et al., 2009), the majority of the existing studies use model-based energy scenario analysis which is considered to be an adequate and useful tool of depicting possible future pathways in energy systems (Krey, 2014). The IPCC's Fifth Assessment Report collected more than 1150 scenarios of future emissions pathways from the peer-reviewed literature (Figure 2-3). Each scenario has its own storyline and assumptions concerning how the future might unfold. The scenarios are classified according to the Representative Concentration

Pathways (RCPs) and the resulting global mean temperature increase. As reflected in the figure, a broad range of energy-related CO_2 emission pathways and the associated temperature change have been discussed in the literature.

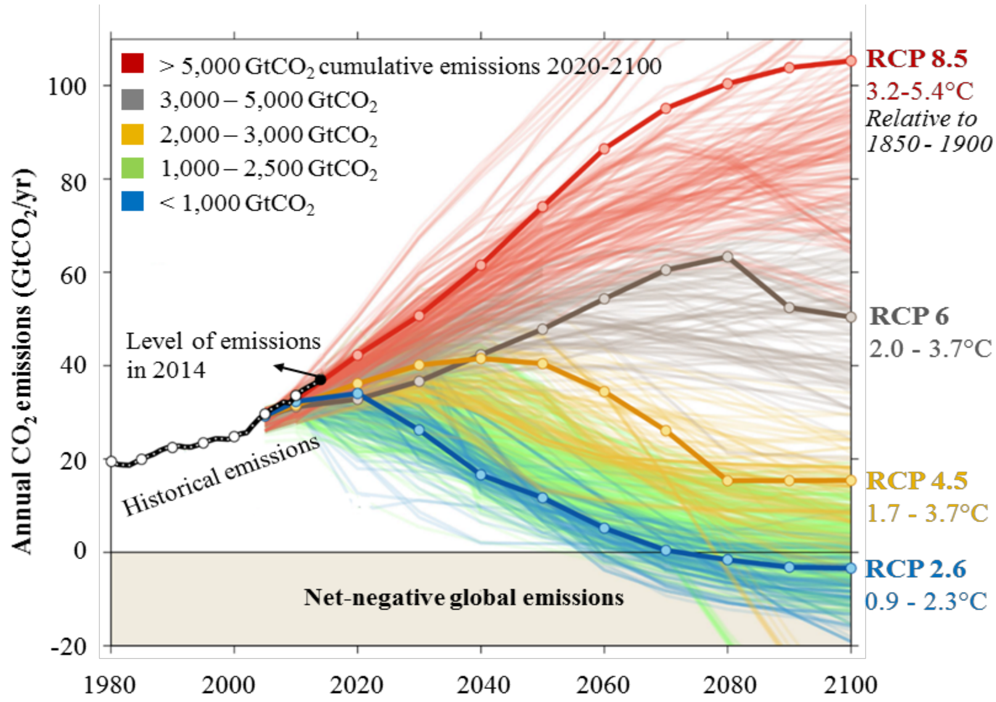


Figure 2-3: Different energy-related CO_2 emission pathways over 2010-2100 and the associated temperature change at the end of the century, from the IPCC fifth Assessment Report – Data source: AR5 Emissions database (2014)

However, a multitude of studies have been carried out to address the role of mitigation measures in reducing CO_2 emissions in the energy sector, using different energy-system models. Generally speaking, there are two widespread modeling approaches, known as ‘bottom-up’ and ‘top-down’. The model classes differ mainly based on the emphasis placed on technological details of the energy system vis-à-vis the interaction between energy and the rest of economy (Böhringer and Rutherford, 2008). As a result, they may provide different insights about energy mitigation pathways and the associated incurred costs. Therefore, to provide a systematic review, studies in this context are categorized based on the employed modeling analytical approach. It is noteworthy that since traditional top-down models suffer from a superficial representation of the energy sector, they are not advisable in the context of this study (E3MLab, 2012). Therefore, although there are few studies that used such models, they are not discussed in this dissertation.

2.3.1 Applications of bottom-up models

In general, bottom-up models focus on energy sector and technological details. Hence, the application of a bottom-up energy model is more suitable to discuss the contribution of technological measures in tackling climate change. As a result, prominent studies in this context have benefited from technology-rich bottom-up models at local, national, regional, and global scales within and among specific energy sub-sectors. At local level, Yang et al. (2015), for instance, used California TIMES energy system model (CA-TIMES) to describe how this state can reduce its emissions in a long-term perspective.

Numerous studies have discussed the contribution of mitigation options, using national and regional energy system models. These studies feature both developed and emerging countries. For instance, Larson et al. (2003) deploying the MARKAL model (the ancestor of TIMES), analyzed future energy-technology mitigation strategies for China in the next 40 years. Blesl et al. (2007) using TIMES model, and Karali et al. (2014) utilizing ISEEM model, investigated the role of efficiency improvement in reducing CO_2 emissions of German industry sector and U.S. iron and steel branch, respectively. AlFarra and Abu-Hijleh (2012), with the aid of the Message model, analyzed the potential role of nuclear energy in tackling climate change of United Arab Emirates (UAE) until the middle of the century.

At the international scale, Odenberger and Johnsson (2010) evaluated the role of CCS technologies in reducing CO_2 emissions of the European electricity sector until the year 2050. The major findings of this study suggest that CCS will be a promising technology for achieving long-term ambitious climate targets of Europe. For the same region, Blesl et al. (2010) using the regionalized Pan-European TIMES model, analyzed the potential role of a broad range of supply-side options encompassing clean technologies, energy efficiency promotions, fossil fuel switching and energy saving. They shed light on the importance of higher penetration of renewables, more extensive use of CCS, and fossil fuel switching. Furthermore, Kawase et al. (2006) conducted an analysis on long-term scenarios for the European climate stabilization. In contrast to the previous study, they took more general measures into account, which are namely energy efficiency, carbon intensity, energy intensity, and CCS. The results of this analysis gave special importance to the former two measures. For the same region, Capros et al. (2012) using PRIMES model, simulated the decarbonization pathways. They highlighted that mitigation strategies that combine all available options are more economical than the strategies which exclude some options.

However, due to importance of tackling climate change at the global level, a vast body of literature has addressed the mitigating role of promising low and zero carbon technologies (i.e., renewables, nuclear, CCS) at this level. Vaillancourt et al. (2008) benefiting from TIMES-World model, discussed the global mitigation role of nuclear energy in reducing emissions and found it as a vital measure. With the aid of TIAM model, Koljonen et al (2009) analyzed the relative roles of CCS, wind and biomass technologies in meeting long-term global decarbonization targets. According to this study all three technology groups will strongly contribute in achieving long-term climate policies. Hong et al. (2015) investigating a range of zero-carbon scenarios across all nations in the world, confirmed that although all of these technologies are required to achieve a decarbonization target, high penetration of nuclear in combination with an appropriate mix of renewables are necessary to meet the target cost effectively. Azar et al. (2006), in contrast, focused on a single option and examined the potential contribution of CCS technology (including Biomass with CCS). In this study, biomass with CCS, which produces negative emissions, was found to be an essential technology for meeting ambitious mitigation goals.

IEA (2016) extensively discussed the relative contributions of renewables, CCS, power generation efficiency and fuel switching, end-use fuel switching, end-use efficiency, and nuclear in meeting 2DS[3] and 4DS[4] climate targets in the period of 2013-2050. As depicted in Figure 2-4, next to end-use efficiency enhancement, renewables were found to be the most vital mitigation to move from 6DS (baseline) scenario to 2°C (2DS) scenario.

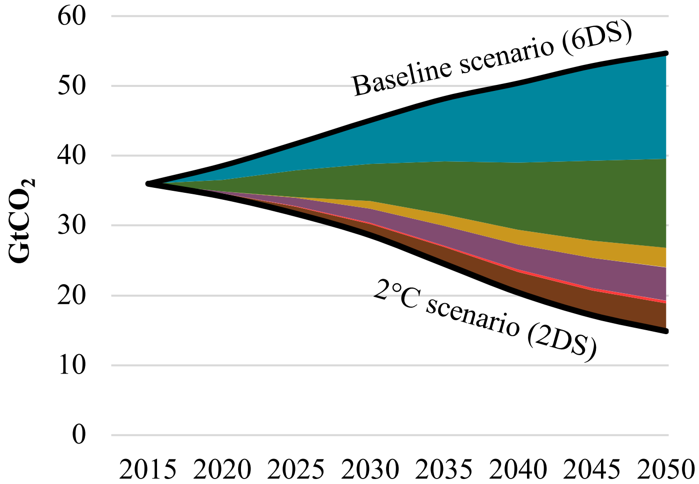


Figure 2-4: CO_2 emissions decomposition between 6DS scenario and 2DS scenario in IEA (2016c)

However, as discussed in the previous chapter, the challenge of meeting long term decarbonization targets cost-effectively not only requires large-scale uptake of low carbon technologies and fuels, but also needs energy-service demand reduction (Webler and Tuler, 2010). In fact, meeting long-term climate mitigation targets imply additional investments in less-carbon intensive technologies and fuels, which will drive up prices for energy services, which consequently reduce energy-service demands. On the other hand, reducing energy-service demands can lead to lower energy consumption and consequently reduce CO_2 emissions in the whole energy system. According to Sorrell (2015), besides improving efficiency, reducing energy-service demand is considered as the most promising, fastest and safest mean to reduce emissions.

A set of different metrics has been frequently used to (implicitly) address the mitigation role of energy-service demand reduction in bottom-up energy system models. However, since

[3] 2DS scenario limits the long-term temperature rise to 2°C compared to pre-industrial levels
[4] 4DS scenario limits the long-term temperature rise to 4°C compared to pre-industrial levels

energy-service demands in such models are (often) given exogenously, they are independent to changes in their prices (Söderholm, 2012). Hence, bottom-up models are not able to explicitly take into account the role that (price-dependent) energy-service demands can play in this context. An attempt to explicitly include the possible interactions between energy-service demands and their prices in bottom-up models, is adding price-elastic demand feature to such models. In the elastic demand version of a bottom-up model, the exogenously defined energy-service demands are replaced with demand curves. The price elasticity parameters indicate how much energy service demands rise/fall in response to a unit change in the marginal cost of meeting the service demands (Anandarajah et al., 2009). In contrast to the standard version, in the elastic-demand version, energy-service demands vary according to changing prices which are induced by a decarbonization policy. While the objective function of the standard version is minimization of total system costs, the demand-elastic version aims to maximize net total surplus of suppliers and consumers (Figure 2-5).

Despite the shortcomings of the demand-elastic approach, such as limited evidence base (Pye et al., 2014), a number of studies have benefited from it. For the MARKAL model generator, this feature was introduced by Loulou and Lavigne (1996). Later, Kanudia and Shukla (1998) employed the demand-elastic version of this model to assess the reaction of energy demands to severe carbon taxes in India. According to this study, up to 10% reduction in India's carbon emission is due to demand reduction. Kesicki and Anandarajah, (2011), in particular, applied the demand-elastic version of the TIAM model to analyze the possible role of energy-service demand reduction to tackle global climate change. In this study, the contribution of service demand reduction in some sectors like transport was found to be around 16%, globally. Using the same methodology, Pye et al. (2014) addressed the uncertainty associated with such energy-service demand responses. They shed light on the essential role of energy-service demand reduction in combating climate change, which ensures a more cost-effective transition to a low carbon energy system.

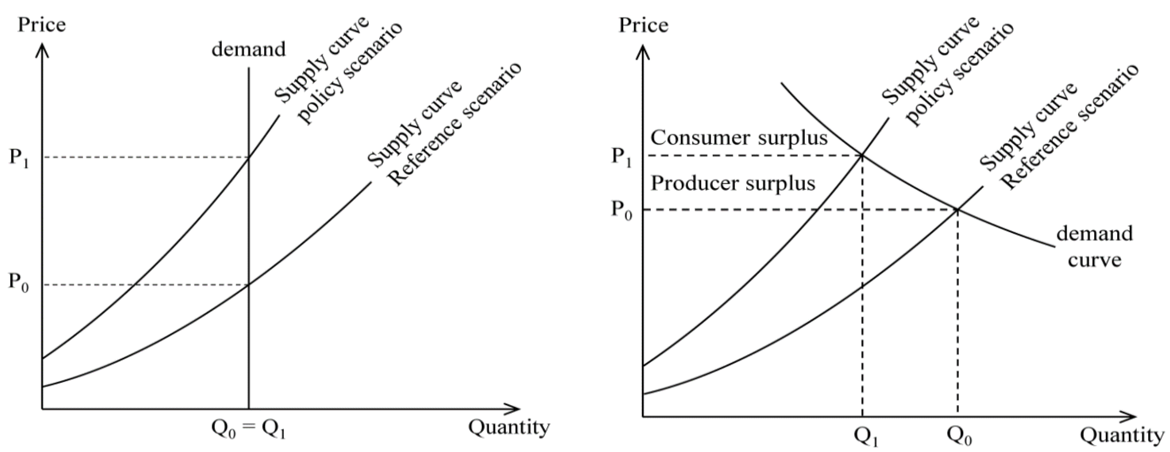


Figure 2-5: Impact of policy-induced price changes on a representative energy-service demand in the standard version (left) and in the elastic demand version (right) of a bottom-up model – Based on Anandarajah et al. (2011)

On the other hand, depending on the level of representation of energy sector and the rest of the economy, different metrics of mitigation costs can be used. One of the widely-applied metrics by bottom-up models is emission marginal price which represents the cost added by reducing one extra unit of emissions. However, this metric does not take into account the full imposed costs of reducing emissions. That is to say, it only deals with direct costs that incurred in the energy system and neglects the macroeconomic implications of carbon reduction policies. In fact, as bottom-up models include only an engineering representation of energy systems, they disregard the interconnection between the energy sector and the rest of the economy. For a deeper assessment of such policies it is of great importance to consider the effects that the policies may have on the whole economy.

On the contrary, top-down models adopt an economy-wide perspective to examine the macroeconomic costs of a policy shock. Therefore, these models are able to consider the macroeconomic mitigation cost metrics (e.g., GDP loss). Table 2-2 presents mitigation cost metrics that have been frequently used in model-based energy scenario studies. A specific model may be able to produce a subset of the given metrics.

Table 2-2: Different mitigation cost metrics frequently used in model-based scenario studies – Based on Krey (2014)

Mitigation cost metric	Description
Carbon or GHG price	Marginal costs of reducing CO_2 or GHG emissions
Additional energy system costs	Additional energy system costs compared to the Base case (without the mitigation policy)
Additional energy investments	Additional investments in the energy sector compared to the Base case
GDP loss	Losses of gross domestic product compared to the Base case
Consumption loss	Losses of household consumption compared to the Base scenario

Despite the described advantage of top-down models, they (mostly) have a limited representation of the energy system (Böhringer and Rutherford, 2008). Hence, the traditional top-down models are not advisable for the analysis of energy-related policies.

To bridge the gaps between the bottom-up and top-down approaches, recently a number of so-called hybrid models have been developed. In essence, a hybrid energy model combines a bottom-up model and a top-down model into a single integrated model framework. The resulting model contains the technological explicitness of a bottom-up model with the economic richness and behavior realism of a top-down model (Andersen and Termansen, 2013). Due to these advantages, hybrid models have recently been extensively used to evaluate mitigation strategies. Chapter 4 discusses the characteristics of the hybrid modeling approach in a detailed manner.

2.3.2 Applications of hybrid models

A vast body of literature has employed hybrid models to explore the role of technological options while considering the associated macroeconomic impacts of the implemented policies. At the national level, Zhang et al. (2014) and Zhu et al. (2015) examined the contribution of CCS, nuclear and renewables in achieving China's climate targets, using REMIND and CE3METL hybrid models, respectively. Both studies shed light on the long-term importance of CCS technology which will significantly affect the level of GDP-losses. Contaldi et al (2007) benefiting from the hybrid MARKAL-MACRO model, evaluated the contribution of renewables in reducing Italy's CO_2 emissions. According to this study, meeting an ambitious decarbonization target requires substantially high investments in renewable technologies (especially biomass), which impose adverse impacts on the GDP.

At the international level, Capros et al. (2014) using different bottom-up and hybrid models, carried out a decomposition analysis on the shares of energy intensity, use of carbon free energies, fossil fuel switching, and GDP in meeting EU climate targets until the year 2050. The results of this study confirm the critical roles of power generation decarbonization, energy efficiency improvements, high penetration of renewables, transport electrification and development of nuclear and CCS technologies. Furthermore, Marcucci and Fragkos (2015) using a set of integrated assessment models, explored short- and long-term drivers of alternative CO_2 reduction pathways in four economies, namely China, India, Europe and USA. According to this study, the major decarbonization strategy is reducing regional carbon intensity, emphasizing on the key role of biomass with CCS.

At the global scale, Duan et al. (2013), with the aid of E3METL (Energy-Economy-Environment model), partially discussed the potential role of CCS in meeting climate targets from technical and macroeconomic perspectives. Further, Van Ruijven et al. (2016) deploying the Timer IMAGE energy-economy simulation model (TIMER), focused on the CO_2 reduction measures in specific industrial branches, namely steel and cement. Based on both of these studies, fossil fuel CCS is essential to achieve ambitious mitigation goals. On the other hand, Kriegler et al. (2014) compiling multiple integrated assessment models, concluded that increased energy intensity improvements and the electrification of energy end use coupled with a fast decarbonization of the electricity sector are robust characteristics of the global energy transformation in the future. In addition, they draw special attention to the role that bioenergy with CCS will play in this context.

On the other hand, there are studies that have looked at the role of demand reduction in meeting long-term climate mitigation ambitions, using hybrid models. However, they mostly stopped at final energy demand[5] and did not continue to energy-services. A very telling

[5] Final energy demand is defined as the quantity of energy (e.g., residential heating) used to provide required energy-services (e.g., residential cooking)

example is the study carried out by Mishra et al. (2014). In this study, the Global Change Assessment Model (GCAM) was deployed to investigate the relative contributions of carbon intensity, energy intensity, structural shift and per capita useful energy measures. Although the authors of the study made note of potential bias of excluding energy services, due to the limitations of the employed model, they did not explicitly consider the role of energy-service demands. However, there exist few studies that have addressed the possible contribution of energy-service demand reduction in tackling climate change, using hybrid models. But, they are limited to the national level. Examples include Chen et al. (2007) and Anandarajah et al. (2009) discussing mitigation pathways and corresponding impacts on the economy of China and UK, respectively. Both of these concluded that energy-service demand reduction is a crucially important to be considered as the level of reductions seems to be significant in decarbonization scenarios.

At the global scale, the only study that dealt with the interactions between energy-service demands and decarbonization target, was carried out by Fujimori et al. (2014) who analyzed the effectiveness of energy-service demand reduction in combating global climate change. However, their study did not explicitly examine the mitigation role that the energy-service demand will play.

2.4 Summary of the state of research of the relative roles of mitigation measures

In summary, for an integrated and comprehensive assessment of climate change mitigation pathways it is essential to consider the mitigation role of technological measures (including renewables, CCS, nuclear, fossil fuel switching, and energy efficiency) with regard to energy-service demand reduction. Furthermore, to provide a more in-depth analysis, macroeconomic implications of the implemented climate policies have to be taken into account. Therefore, this dissertation aims at filing the existing gaps in the literature and evaluates the relative contributions of all the aforementioned measures in meeting global long-term climate mitigation targets, considering the associated macroeconomic impacts.

Table 2-3: Examples of studies on mitigation measures and the existing gap in the literature

Study	Mitigation measures				Whole Economy coverage	Modeling approach
	Efficiency improvement	Low-carbon technologies	Fossil fuel switching	Service demand reduction		
Blesl et al. (2007)	✓					Bottom-up
AlFarra and Abu-Hijleh (2012)		✓				Bottom-up
Blesl et al. (2010)	✓	✓	✓			Bottom-up
Koljonen et al. (2009)		✓				Bottom-up
Kanudia and Shukla (1998)				✓		Bottom-up
Kesiki and Anandarajah, (2011)				✓		Bottom-up
Zhang et al. (2014)		✓			✓	Hybrid
Capros et al. (2014)	✓	✓	✓		✓	Hybrid
Duan et al. (2013)		✓			✓	Hybrid
Kriegler et al. (2014)	✓	✓	✓		✓	Hybrid
Chen et al. (2007)	✓	✓	✓	✓	✓	Hybrid
This dissertation	✓	✓	✓	✓	✓	**Hybrid**

3 The energy system model TIAM

This chapter presents the underlying modeling framework of TIAM. It starts by illustrating a general picture of energy system analysis and energy scenario analysis. Furthermore, energy models as tools that facilitate the work with energy scenarios studies are discussed. In order to understand and interpret the results of these models, a number of criteria for classifying energy system models are presented in the next section. Subsequently, the TIMES model generator and its main elements are explained. Finally, this chapter presents the model structure of TIAM, followed by a brief overview of its applications in peer-reviewed journal papers.

3.1 Energy system analysis

In its wider conception, the word 'system' refers to as "a complex of interacting components together with the relationships among them that permit the identification of a boundary-maintaining entity or process" (Laszlo and Krippner, 1998; P.2). The term 'energy system' is described as a process chain from primary energy suppliers over transformation, processing and distribution of energy carriers to energy demands (Pfenninger et al., 2014). Accordingly, energy system analysis can be defined as an investigation of the structural characteristics of an energy system through analyzing the descriptive representation of its functions (Voß, 2009). In contrast to the assessment of a single element (e.g., a technology), system analysis focuses on structural elements of the whole system and their interactions, which are essential for understanding how the system may behave under different conditions. It can be argued that the main purpose of the energy system analysis is to support decision making in a wide variety of energy-related issues, considering the associated assumptions and limitations. Climate change mitigation, sustainable development, and management of limited fossil fuel resources are some examples of issues that can be taken into account in an energy system analysis.

However, highly uncertain and complex nature of present and future energy systems evokes challenges for the energy system analysis. That is to say, within an energy system a number of key elements exist that interact in a complicated manner. Furthermore, knowing that these elements possess a dynamic nature, they may vary over time unexpectedly. One possibility to deal with such challenges is 'scenario analysis. A definition of the word 'scenario' is given by IPCC:

"A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships" (IPCC, 2007, P. 86).

Lempert (2003) introduced scenario analysis as a suitable method to deal with what is called "deep uncertainty". According to Cao et al. (2016), energy scenarios have two main purposes: first, to facilitate discussions about energy futures; second, to support decision-makers in the context of strategic energy planning. In other words, scenario analysis can be seen as "a useful tool to help decision-makers in government and industry to prepare for the future and to develop long-term strategies in the energy sector" (Dieckhoff et al., 2011, P.89).

3.1.1 Energy scenario study

Despite the old concept of scenario, the origin of its application as a planning tool goes back to around 40 years for military purposes (Bradfield et al., 2005). At that time, the main reason for using scenario analysis was to manage risks and develop robust strategic plans in the face of an uncertain future. However, due to radically increasing importance of energy-related issues (e.g., climate change mitigation), recently, scenarios have mostly been used in the context of energy planning. As a result, the number of energy scenario studies published in recent years has risen tremendously. In 2011, for example, the European Environment Agency (EEA) listed 263 scenario studies (EEA, 2011).

In the context of energy research, energy scenarios are important means providing useful input to policy-relevant assessment reports (Krey, 2014). The main objective of energy scenario study is to develop and compare a set of strategic choices under a variety of plausible futures. According to Wilkinson (2004), energy scenarios are not intended to predict the future; instead, they highlight the main driving forces that push the future into different directions. Therefore, energy scenarios aim to make the driving forces visible by providing qualitative insights rather than numbers. (Weyant, 2009; Huntington et al., 1982).

In general, there are two approaches for developing scenarios: 'exploratory' and 'normative'. The distinction is based on principal questions that a user may ask about the future. The former scenario type begins with the present as the starting point, and moves forward to the future by asking 'What if?' questions about driving assumptions (e.g., GDP growth rate). As illustrated in Figure 3-1, a trumpet of various conceivable explorative scenarios forms the 'possible future space'. 'Business as usual' is the most-likely explorative scenario, which is (mainly) based on the extrapolation of the past trend. In fact, when conditions are stable, forecasting and planning the future are relatively simple. However, when unexpected and abrupt changes occur, such a simple projection is no longer valid and may provide biases that lead to poor decisions.

Contrary to the explorative approach, the normative approach starts with a possible desirable future by asking 'How can the possible desirable future be reached?' That is to say, normative scenarios push the world toward a target such as a particular level of carbon emissions in the atmosphere. In the past, researchers have mostly used the normative approach to develop scenarios. However, today the given distinction is highly simplified and most of the energy scenarios are built by a combination of both approaches.

According to Grunwald (2008), in order to derive rational policy recommendations, it is of crucial importance to consider both the selection of plausible measures to reach certain target(s) and interconnections between those measures. It is noteworthy that energy scenarios are mostly served as points of comparison to analyze sensitivities of outcomes. Single scenarios are therefore rarely useful and should be rather combined with and compared against other scenarios (Mai et al., 2013).

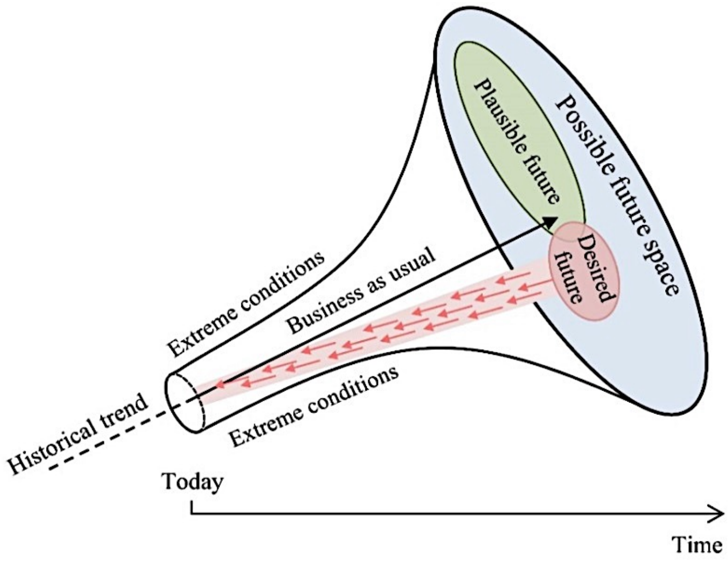


Figure 3-1: The scenario trumpet showing different type of scenarios – Based on Reibnitz (1991)

A tool that is closely bound up with energy scenario analysis is 'energy model'. In general, 'model' is defined as a mathematically consistent framework including an inter-dependent set of equations (usually in the form of computer algorithms), which aims to depict how a phenomenon occurs in a complex system[6]. Energy models are consistent and streamlined representation of real world systems, which are used to explore how the energy systems develop under certain assumptions and limitations. According to WEM (2014), energy models are especially suitable for the condition that conducting experiments in the real world are impractical, impossible or too costly.

Although we cannot say energy scenario studies necessarily require energy models, due to the complex and interwoven nature of energy systems, mostly these studies benefit from energy models (Pfenninger et al., 2014). Strictly speaking, the development and application of a formal energy model which may capture quantitative and qualitative aspects of the system, facilitates the work with energy scenario studies.

Figure 3-2 illustrates a conceptual framework of the typical steps of conducting a model-based energy scenario study from collecting and preparing empirical data (also called statistical data) over assumption-making, model(s) application and preparation of model(s) outputs for the presentation of results to comprehensive conclusions and recommendations. As depicted, empirical data can be divided into primary input data which is imported to the model directly and secondary input data which needs pre-processing before being imported. The model

[6] Krakauer (2013) defines complex systems as ones that do not yield to compact forms of representation

exercise contains at least one model (here called 'model A'). However, in some cases (such as this Dissertation) a combination of two models or more is applied (for simplicity, here a combination of only two models via a link stream is depicted). Similar to input data, outputs are divided into primary and secondary data. Moreover, this figure illustrates that assumptions can be taken for the model as well as optionally for the pre-processing, post-processing, additional applied model(s) and link(s) between models. Results represent the last step of the model exercise. They are given based on the model's final output data. Finally, conclusions and recommendations are made based on the whole chain from the empirical data to the results.

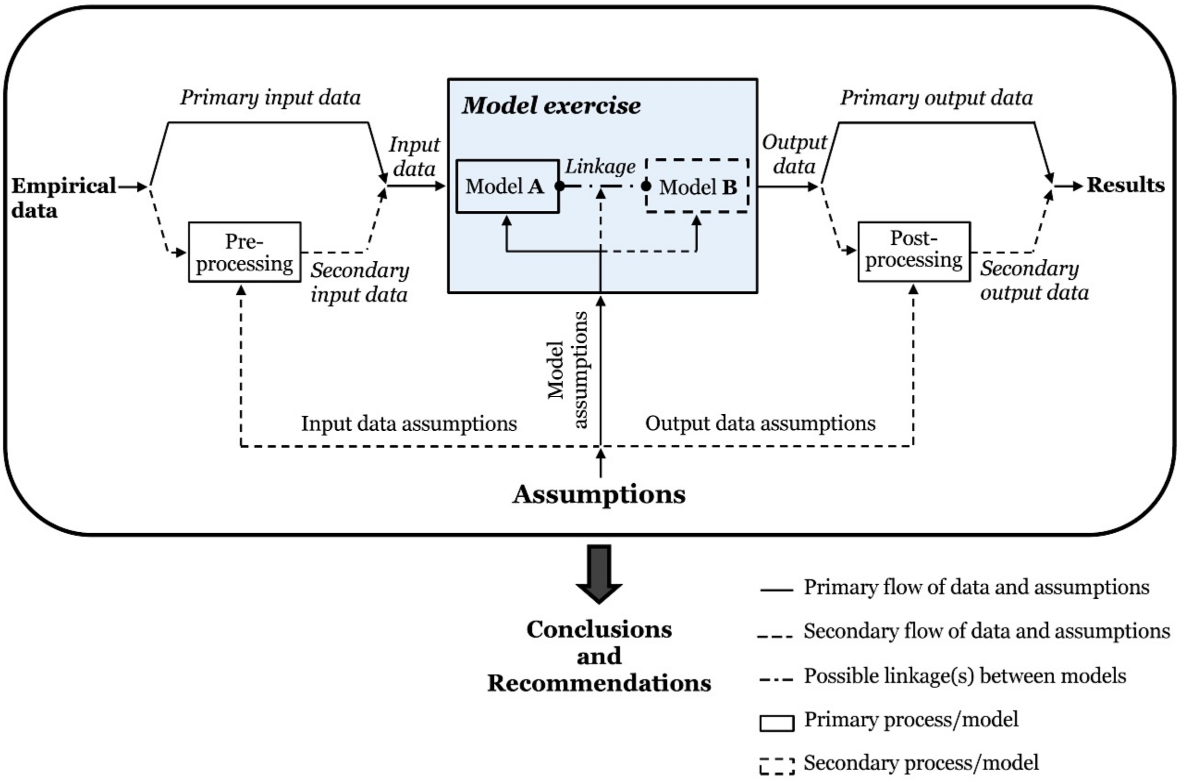


Figure 3-2: Information flow and data processing within a model-based energy scenario study – Own figure published in Cao et al. (2016)

3.1.2 Energy models

Since the oil crisis in the early 1970s, energy discussions became controversial challenging issues in the societies of almost every nation in the world. Even though the use of energy models can be traced back to a decade before the oil crisis, this event was the main reason for the growing awareness of energy-related problems, which led to a widespread development in energy modeling (Rath-Nagel and Voß, 1981).

Energy models have been predominantly developed to plan future scenarios and to analyze the energy systems at different geographical scales (Laha and Chakraborty, 2017). Some primary energy models focus on a specific sub-sector (e.g., power suppliers) or an energy carrier (e.g., oil) (Bhattacharyya and Timilsina, 2009). Furthermore, some models cover multiple subsectors or fuels, but they consider only supply-side or demand-side part of the system. Such models are mostly used in an exploratory manner to project the future energy demand or supply of a country or a region. However, since they do not include possible interactions between the focused sub-system with the rest of the energy system, their results may contain biases (Rath-Nagel and Voß, 1981). This criticism is the major motivation of shifting from conventional energy models to energy system models that cover all energy flows from primary energy suppliers over different conversion and transformation processes toward final end-use demands. An energy system model acts as a tool for transforming a very complex energy system into a simpler, yet representative form (NEP, 2010). This makes the scenario analysis easier, which in turn, leads to a better and more comprehensive decision-making.

In recent times, due to the increasing importance of energy-related issues as well as the expanding computation power, the number of total available energy models has grown tremendously. The models are not in a homogeneous group of tools and may differ in various dimensions. Over years, several studies (e.g. Beeck, 1999; Jebaraj and Iniyan, 2006; Bhattacharyya and Timilsina, 2009) have provided numerous categorization schemes in order to identify similarities and differences between the energy models. Such classifications are beneficial for interpretation of model results (Weyant, 2009). Moreover, they are important tools for communicating, comparing and developing energy models (Börjeson et al., 2006).

According to Laha and Chakraborty (2017), initially three modeling classes including optimization models, equilibrium models, and simulation models, have been identified. Later, several other dimensions have been taken into account. Figure 3-3 gives a comprehensive literature survey on classifications of energy models. As depicted, ten different categories can be considered: the purpose of constructing the energy model (i.e., to normatively investigate pathways to desirable futures or to explore possible developments regardless of their desirability); the analytical approach (i.e., engineering bottom-up, or economic top-down); the methodology (e.g., optimization, simulation, economic equilibrium, econometrics); the programming technique (e.g., linear, nonlinear, dynamic, mixed-integer); the mathematical logic (i.e., deterministic, stochastic, fuzzy, interval); the geographical coverage (e.g., project, local, national, regional, global); the general sectoral coverage (i.e., whether the entire economy is modeled or only the energy sector); the energy sectoral coverage (i.e., whether the whole energy system is modeled or sub-sector(s) of it); the time horizon (from short-term to long-term); the level of time resolution (from low to high).

In the context of climate change mitigation, one of the important dimensions is the analytical approach. As discussed in the previous chapter, in general, bottom-up models are partial equilibrium representations of the energy sector that look at the energy system from a technological perspective. They use disaggregated data to represent the whole energy system encompassing all necessary current and future technologies from primary energy supply to energy demands in different end-use sectors via multiple processes of conversion, transport, and distribution. Bottom-up models contains a large number of discrete energy technologies which are described by means of economic parameters (e.g., investment cost), technical data (e.g., capacity, efficiency and lifetime), and environmental parameters. Hence, for a systematic analysis of the required transformations in the energy system and the associated direct costs in order to achieve climate mitigation targets, it is essential to deploy a bottom-up energy system model.

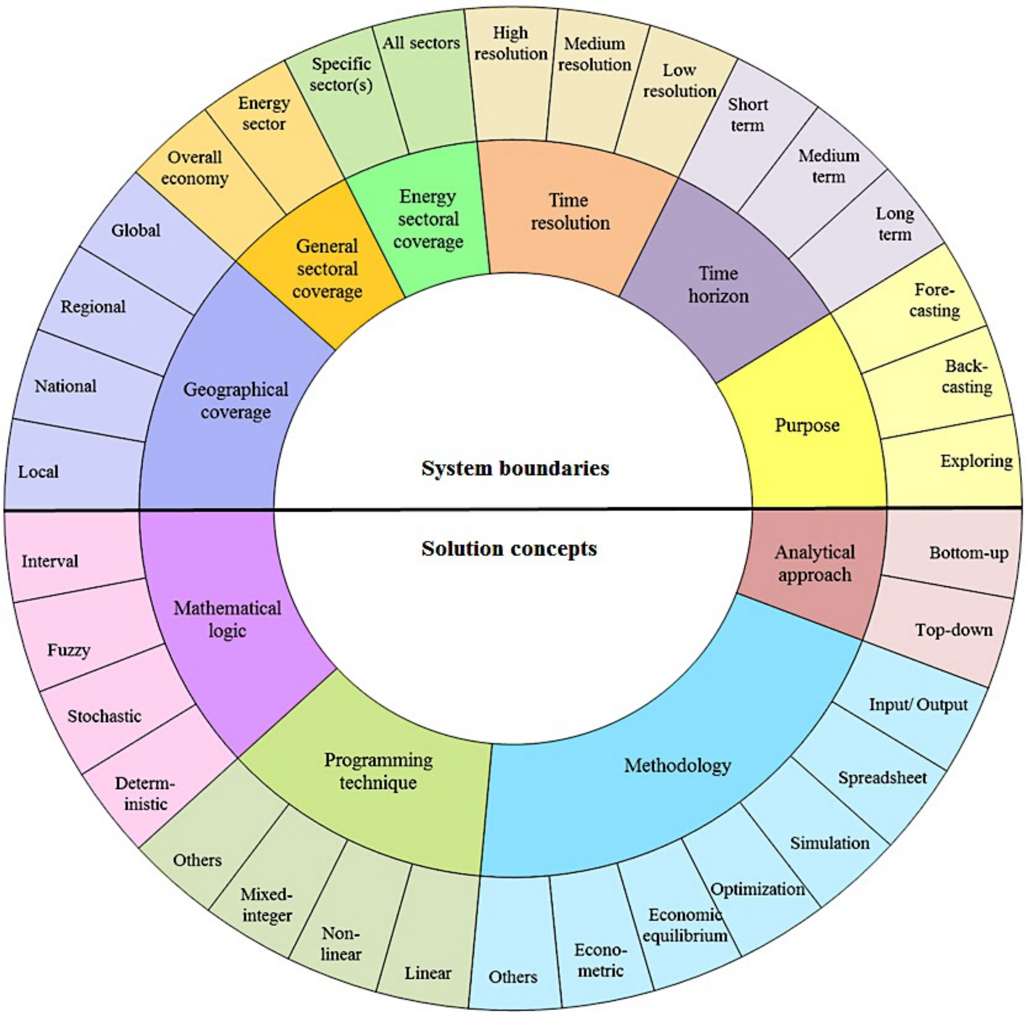


Figure 3-3: Classification of energy system models – Based on Beeck (1999); Jebaraj and Iniyan (2006); Bhattacharyya and Timilsina (2009); Krey (2014)

3.2 The TIMES model generator and its features

MARKAL (MARKet Allocation model) as the most widely applied general energy system model (Pfenninger et al., 2014), with the addition of another optimization model, EFOM (Energy Flow Optimization Model), evolved into a new model called TIMES (The Integrated MARKAL-EFOM System). TIMES model generator was developed and is maintained on a collaborative effort by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA). According to Bradley (2014), TIMES models are being used by more than 250 institutions in 70 countries around the world for different energy-environment related purposes.

TIMES is a bottom-up, partial equilibrium, linear least-cost optimization energy system model generator. The main building blocks of a TIMES model are technologies and processes which are connected by commodity flows. The overall objective of the model generator is to supply a set of (exogenously specified) energy-service demands in different end-use sectors, at minimum overall costs (i.e., minimum total discounted energy system costs) subject to a set of technical, social and political constraints. The total annual energy system costs include investment and dismantling costs that are annualized using hurdle rates, annual fixed, maintenance and variable operation costs, net export costs (in multi-regional models), and costs related to commodity flows. Besides, the salvage value of processes at the end of the planning horizon is also considered. The annual costs are discounted to the present and then aggregated into a single objective function (Eq. 3-1).

$$NPV = \sum_{r=1}^{R} \sum_{y \in years} (1 + d_{r,y})^{refy-y} \cdot ANcost\,(r,y) \qquad \text{Eq. 3-1}$$

Where,

R	total number of regions
NPV	net present value of the total costs
$d_{r,y}$	discount rate in region *r* and year *y*
refy	reference year for discounting
ANcost (r,y)	total annual cost in region *r* and year *y*

The model is able to consider multi-stepped supply curves. Each step represents a certain potential for a resource at a particular cost. For some energy carriers, the potential may be defined as a cumulative potential over the time horizon (e.g., reserves of gas and oil), as an annual potential (e.g., annual biomass potential) and as a cumulative potential over the resource base (e.g., available roof arias for PV installations). In multi-regional incarnations of the model generator, trading possibilities of different energy-carriers are taken into account. The amounts of traded commodities and the associated costs are calculated endogenously based on user-specified assumptions and constraints.

The user of a TIMES model provides three types of input data which ultimately determine the model structure. The first type is statistical data referring to the characteristics of existing stock of energy-related equipment, as well as current sources of primary energy supply used in the base-year. The second required input data is assumptions that cover the technical, economic and environmental specifications of future technologies and fuels, as well as regional trades (if multi-regional), characteristics of future primary energy supply sources (including their potentials), projection of energy service demands and specific assumptions concerning the entire reference energy system (e.g., discount rate). Constrains are the third type of input, which reflect known limitations and policies that force something to happen or prevent something from occurring, such as phasing out of nuclear or cutting down emissions to a desired level.

The TIMES model generator is implemented within the modeling environment GAMS (General Algebraic Modeling System) and solved via linear programming solvers (e.g., CPLEX, XPRESS). ANSWER, VEDA-FE, and VEDA-BE are three user-friendly interfaces used to handle the input data (e.g., techno-economic description of technologies, projection of energy-service demands and primary energy resource potentials) and process the output data (e.g., annual primary energy consumption, CO_2 marginal abatement cost) (Noble-Soft 2011; Kanors 2011). Figure 3-4 shows the process of applying a TIMES model from reference energy system to final results.

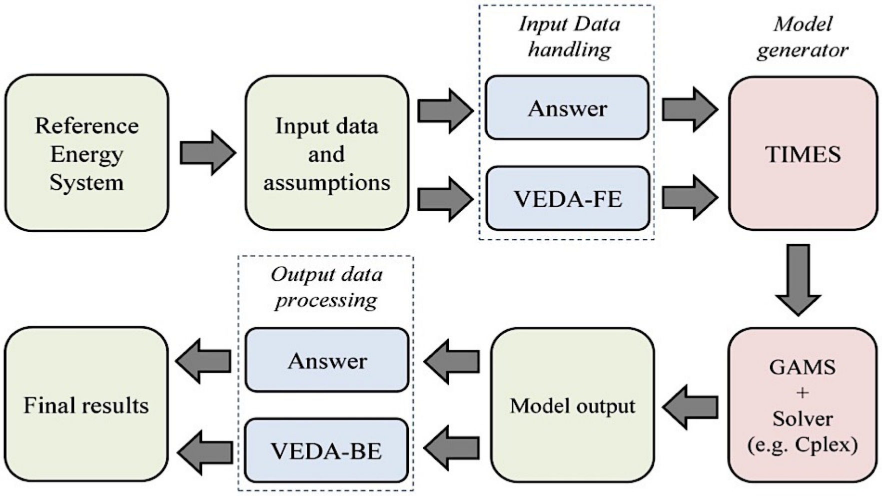


Figure 3-4: Application process of a TIMES model

The dynamic part of a TIMES model is determined by the time horizon and time resolution, the growth rate of the demand for energy-services, and policies (e.g., CO_2 reduction targets), complimented by various alternate scenarios (Anandarajah et al., 2011). The standard TIMES model assumes ‘perfect foresight’ - all market participants are assumed to have perfect inter-temporal knowledge of future energy-related issues and economic developments. Moreover, the model assumes ‘perfect competition’ which arises when the conditions described in Table 3-1 are met.

TIMES is a flexible model generator in terms of geographical coverage and number of regions. This is reflected in its applications varying from cities to world modeling approaches. On the other hand, while some existing TIMES models cover the entire energy system, some others focus on a single sector (e.g., power generation).

Table 3-1: Specifications of perfect competition – Based on Parkin et al. (2005)

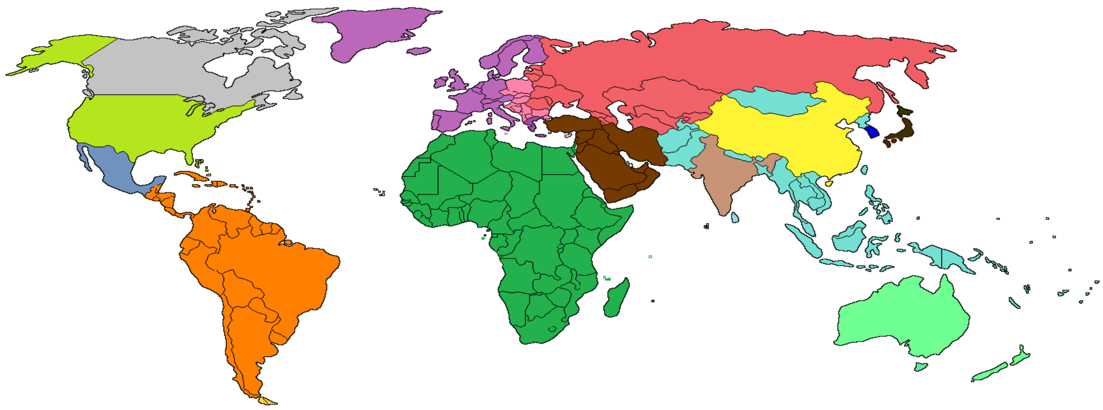
Criteria	Specification(s)
Number of firms	• Many different firms sell an identical product
Firm differentiation	• Existing firms have no advantage over new ones • Decisions to buy goods/services are made according to prices
Price mechanism	• No individual seller/buyer is able to exert a significant influence on prices • Both sellers and buyers are well informed about prices
Restrictions on entry/exist	• No restriction on entry into and exist from the industry • Resources are easily exchanged among industries

Despite the strengths of the TIMES model generator, namely the detailed representation of the energy system and the application flexibility, it is often criticized for the assumptions of perfect foresight and perfect competition (Schönfelder et al., 2011; Möst et al., 2008). Further, the models represent the perspective of decision-makers under optimal condition over the long-term planning horizon. Nevertheless, given the number of political, financial and behavioral limitations, as well as uncertainties in the real world, investors and individuals do not behave under optimal conditions (Gambhir et al., 2014). Thus, the calculated energy costs by such models should be seen as a lower bound of the real system costs. However, new features have recently been added to the model to address such criticism. For instance, TIMESTEP is an additional feature that runs the models in a stepwise manner with a 'myopic' or limited fore-sight perspective and optimizes only certain time periods together, nor the whole time-horizon. For a more detailed description of the TIMES model generator please see Loulou et al. (2016a), Loulou et al. (2016b), Goldstein et al. (2016) and Gargiulo et al. (2016).

3.3 General model structure of TIAM

Considering the high detailed representation of current and future technologies and fuels in the energy system, the TIMES model generator is admirably suited to study energy-related policies. However, the choice of the system boundaries is determined according to the research question in order to fully address interconnections relevant to the system. Considering the fact that actions to tackle climate change should be taken based on international agreements at the global level rather than solely national and regional policies (Jewell, 2013), in this study TIAM (TIMES Integrated Assessment Model), as a global incarnation of the TIMES model generator, is applied.

TIAM consists of 15 regions which are depicted in Figure 3-5. The model is, however, flexible to aggregate or to further disaggregate the existing regions. For instance, TIAM-UCL (Anandarajah et al., 2011) is a 16-region version of the TIAM model containing UK as an explicit region with its own energy system. It is important to note that a limited number of regions has advantages for analysis of long-term global scenarios and reduces uncertainties of the associated assumptions on regional developments. In contrast, considering the fact that decisions are usually taken at the national level, high aggregation of regions restricts the ability of modeling national policies.



Africa
Australia
Canada
China
Central and South America
Eastern Europe
Western Europe
India
Japan
Mexico
Middle East
Other Asian countries
South Korea
USA
Former Soviet Union

Figure 3-5: The regions of the TIAM model

For a better representation of primary energy resources, the regions are further divided into OPEC and Non-OPEC groups. For each region, the model describes the entire energy system by all necessary current and future energy technologies from primary energy suppliers over transformation, processing, distribution technologies of energy carriers to a set of energy-service demands within residential, commercial, agricultural, industrial and transportation end-use sectors. Figure 3-6 depicts the simplified structure of so-called Reference Energy System (RES) for each region of the model. The RES includes all the main energy, material and emission flows in the energy system. However, each of the presented sectoral blocks in the RES encompasses various energy and process technologies. In total, each region includes about 1500 different existing and new technologies (Syri et al., 2008).

The model covers primary energy resources of fossil fuels (oil, gas, coal) as well as nuclear and potentials for renewable sources. Gas and oil reserves are divided into four major groups: located reserves, producing pools; enhanced discovery (reserve growth); and new discovery. Unconventional and non-connected gas reserves including coal bed methane, tight gas aquifer gas and shale gas are characterized. Four types of oil reserves are considered: light oil, heavy oil, oil sand and shale oil. For each type of oil and gas reserves a three-step supply curve is modeled. Each step is modeled by the cost of the resource and the level of available energy at the given cost. Further, coal resources are divided into hard coal and brown coal. For each, located and new discovery reserves are considered. The uranium reserves are modeled cumulatively in each region, for which two steps of extraction are included.

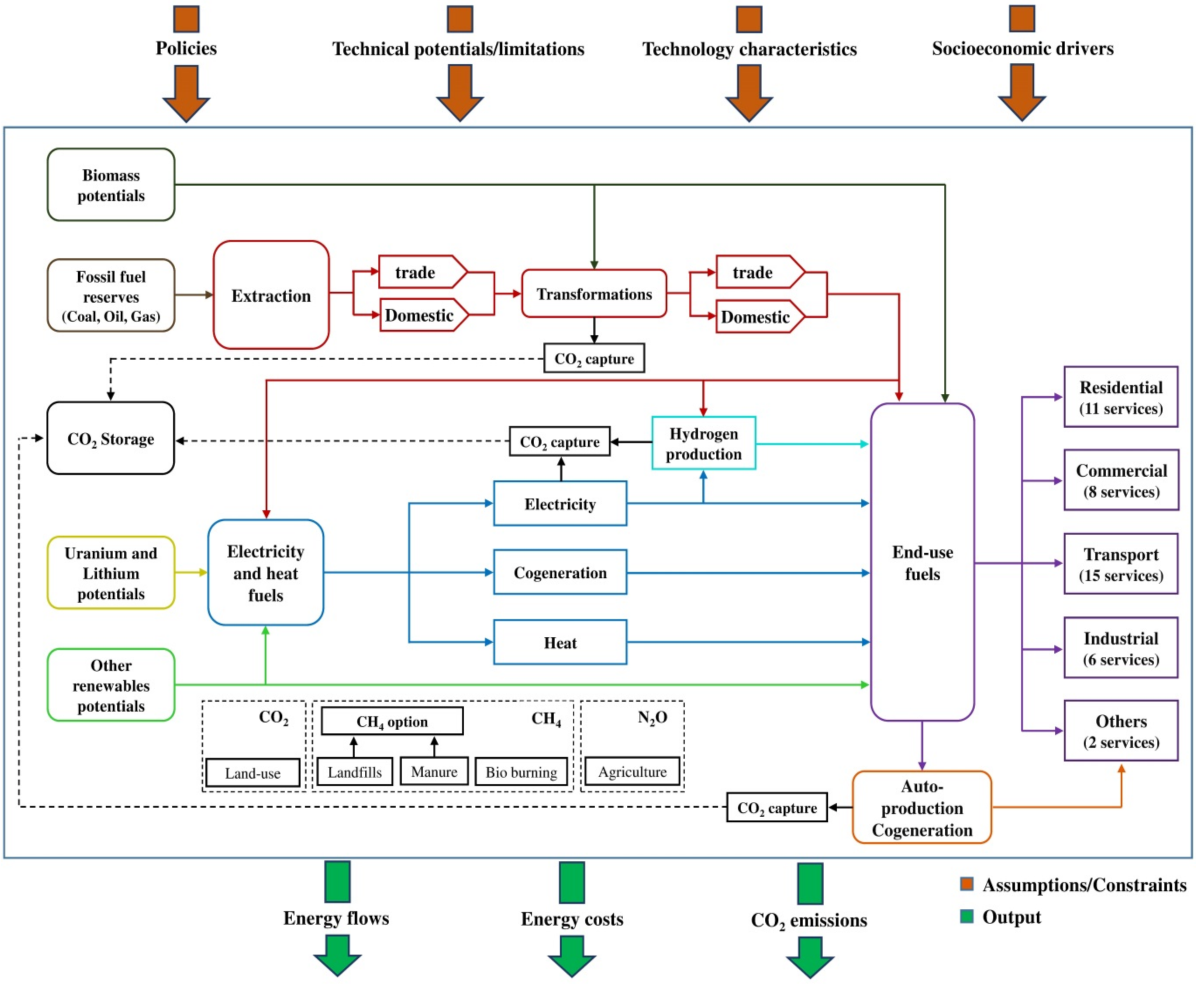


Figure 3-6: A simplified representation of reference energy system of the TIAM model

The model regions are connected through trade links of hard coal, crude oil, liquefied natural gas (LNG), natural gas, refined petroleum products (gasoline, diesel, heavy fuel and naphtha) and nuclear fuels. Thus, the prices of all these commodities are determined endogenously in the model. Emissions can be traded across all regions via a central trading body which allows for carbon credits to be sold from one region to the next.

The electricity and heat generation sector encompasses many different technology types, using a wide range of fossil fuels, nuclear and renewable sources. Renewable electricity sources include wind (offshore and onshore), hydro (large, small and mini), solar Photovoltaic (PV) and Concentrated Solar Power (CSP), geothermal, tidal, wave and biomass (solid biomass, biogas, energy crops, municipal waste and industrial waste).

According to the type and purpose of production, the electricity and heat sector is divided into six different groups (presented in Figure 3-7).

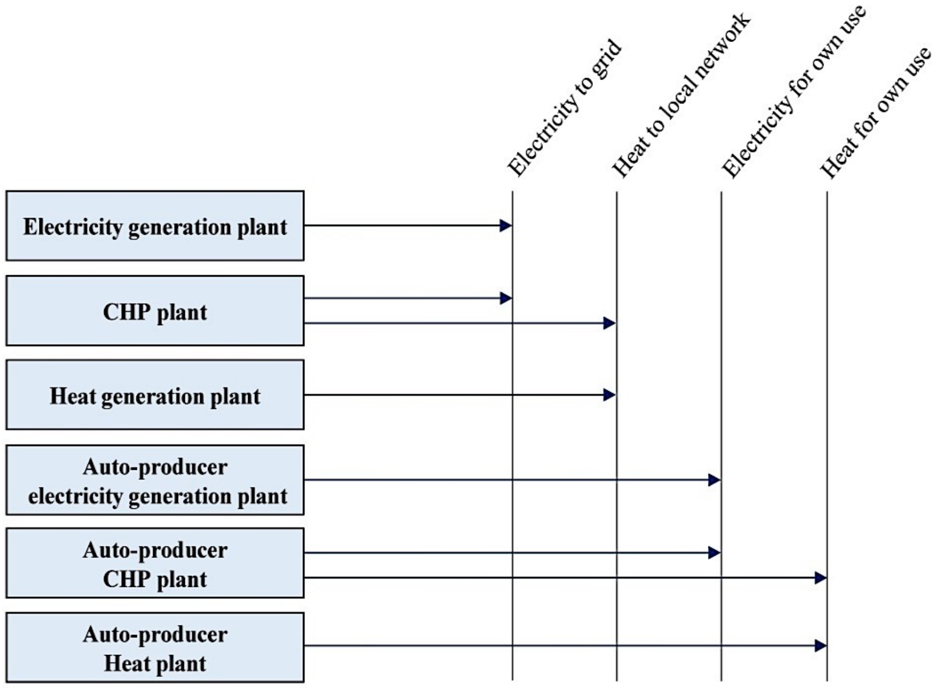


Figure 3-7: The electricity and heat generation technology types in the TIAM model

Power plants are additionally classified as providing electricity to centralized or decentralized grids. Centralized generators tend to be large-scale, usually located away from end-users and are connected to high-voltage transmission networks. The generated electricity by these power plants is distributed through electric power grids to the end-users. In contrast, decentralized generation refers to small-scale generation of electricity, connected directly to the distribution network or local grids. Rooftop solar photovoltaic is an example of decentralized electricity generators.

CO_2, CH_4, N_2O emissions from fossil fuel combustion are modeled, using emission coefficients. The majority of the non-CO_2 gases come from the agricultural sector (IPCC, 2007b) and therefore are not directly related to the energy sector. Hence, they are introduced into the model, using exogenous assumptions. Moreover, compared to the available mitigation options for CO_2 emissions, notably fewer options are modeled for mitigating the non-CO_2 gases. Hence, the model is able to provide more insight into CO_2 mitigations mitigation analysis rather than all GHG emissions.

Several carbon capture and storage technologies coupled to fossil fuels and biomass in the electricity, industry and synthetic fuel production sectors are retained in the model. Besides biomass with CCS, there are other options that deliver negative emissions such as direct air capture, biochar, enhanced weathering, augmented ocean disposal and lime-soda process (EASAC, 2018; McGlashan et al., 2012). However, as their cost and potential are highly uncertain, they are not included in the current version of TIAM.

CCS includes three main processes: CO_2 capture, compression, transport, and storage. While the model considers the capture and storage processes, it does not implicitly contain compression and transport processes. However, the associated costs of these processes are comprised.

To store the captured CO_2 emissions, several storage alternatives, including depleted oil and gas fields, enhanced oil recovery, coal-bed methane recovery and deep saline aquifers, are modelled. For each storage type, theoretical cumulative capacities are specified by regions with a distinction between onshore and offshore storages.

Generally speaking, implementation of a mitigation target in the model is often represented by two complementary approaches: a total emissions abatement constraint or a carbon tax. In fact, once the emissions reduction constraint is imposed, the carbon tax becomes a dual variable to the constraint, determining the Marginal Abatement Cost (MAC). In addition, the model includes an integrated climate module that uses a set of equations to compute the changes in concentrations of the GHG emissions in the atmosphere plus the upper and lower parts of the ocean, the total changes in atmospheric radiative forcing and induced changes in global mean surface temperature compared to pre-industrial levels. The module is inspired by the Nordhaus and Boyer model (see: Nordhaus and Boyer, 1999).

Given the fact that stabilization of climate takes several decades to a century, the time horizon of global energy models (which are mainly applied to evaluate mitigation strategies) need to be on this order. Accordingly, the TIAM model covers a time horizon from 2005 to 2100, which is divided into ten periods. The model splits each time period into six time slices consisting of three seasons, namely, summer, winter, and intermediate with equal length (i.e., four months). To consider changes in load based on sector demand profiles, each season is further divided into day and night accounting for 16 hours and 8 hours, respectively (Figure 3-8).

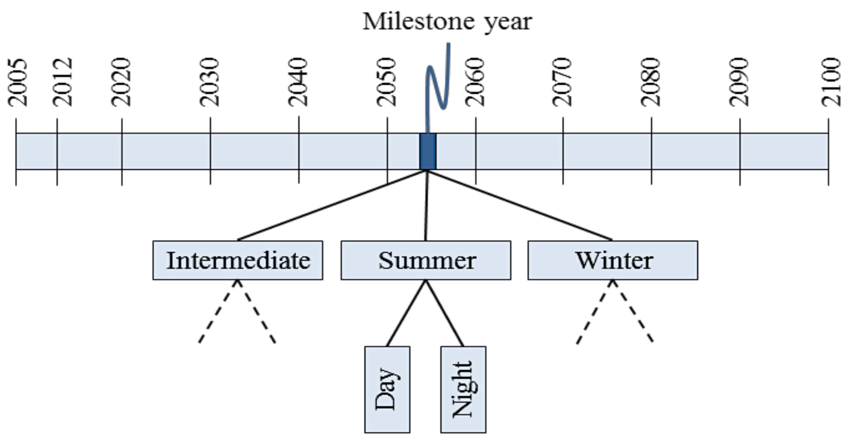


Figure 3-8: Temporal resolution implemented in the TIAM model

Depending on the purpose of the study, the model is flexible to increase the number of inter-annual time-slices. This allows a much more detailed representation of variations in energy demand and supply, including operating characteristics of specific technologies.

Considering the objective function of the model (i.e., minimization of total discounted system costs), a model parameter that plays a critical role in evaluating future costs and reimbursements of the energy system is the (social) discount rate. The selection of an appropriate value for this parameter is crucial because it affects the assessments of system costs, technological preferences, mitigation measures and policies (Goulder and Williams, 2012). The higher the discount rate, the lower the present value of the future costs.

3.3.1 Energy-service demands in the TIAM model

TIAM comprises 42 energy-services in the five end-use sectors (Table 3-2). To fulfill each energy-service demand, a number of technologies exist. The technologies vary in terms of input fuel(s), efficiency and costs. Table A-4, Table A-5 and Table A-6 in the Appendix present the number of technologies and the associated fuel alternatives of the energy-service demands in the model. For instance, in order to fulfill the demand of residential hot water, 20 technologies exist that consume electricity, heat, fossil fuels (e.g., natural gas) and renewables (e.g., solar).

The given distinction of energy-services in TIAM is line with the definition of 'energy-service' in the chapter 1. In fact, each of the energy-services is treated as a function that consumes energy to satisfy the demand for a service (e.g., demand for auto transport, measured in billion vehicle kilometers). Similar to other bottom-up models, the energy-service demands in TIAM are projected exogenously. They are specified at the regional level based on a range of exogenously-given drivers such as GDP, GDP per capita, GDP per household and population. The energy-service demands are linked to the underlying drivers, using elasticity factors. The elasticity factors reflect the sensitivity of energy-service demands to a change in their underlying drivers. Usually, the assigned elasticities are less than one, highlighting that the energy-service demands grow slower than the underlying drivers.

As the energy-service demands in the TIAM model are projected exogenously, they are independent to their prices. This means that the projection of an energy-service demand is fixed unless either the driver or the elasticity parameter changes. Therefore, although TIAM shows how the energy-service demands can be satisfied at the lowest possible cost, it is not able to reflect the 'price effect' which refers to the impact of a change in energy prices on the demand of energy services (Parkin et al., 2005). Hence, although the model provides a detailed technological representation of the energy system, it is not able to address the contribution of (price-dependent) energy-service demands in tackling climate change. However, as earlier discussed, for a comprehensive and integrated assessment in the context of climate change mitigation, besides the technological measures, it is essential to look at the role of energy-service demand reductions.

Table 3-2: Energy service demands in the TIAM model

***Residential segments* (11)**	Pulp and paper
Space heating	Chemicals
Space cooling	Non-metal minerals
Water heating	Other industries
Lighting	***Transportation segments* (15)**
Cooking	Auto
Refrigeration	Bus
Clothes washing	Light truck
Clothes drying	Commercial truck
Dish washing	Medium truck
Electric appliances	Heavy truck
Other energy uses	Two-wheeler
***Commercial segments* (8)**	Three-wheeler
Space heating	International aviation
Space cooling	Domestic aviation
Water heating	Rail-freight
Lighting	Rail-passenger
Cooking	International navigation
Refrigeration	Domestic navigation
Electric equipment	Non-energy uses in transport
Other energy uses	***Other segments* (2)**
***Industrial segments* (6)**	Agriculture
Iron and steel	Other non-specified uses
Non-ferrous metals	

4 The hybrid energy system model TIAM-MACRO

This chapter presents the underlying modeling structure of the hybrid energy system model, TIAM-MACRO. It starts by elaborating the general concept of hybrid energy system modeling. Accordingly, it shows that compared to conventional bottom-up models, hybrid energy models provide deeper insights into the investigation of climate change mitigation pathways. In the next section, the general structure of the MACRO model is discussed, followed by a review of its applications. Finally, the overall structure and the main equations of the TIAM-MACRO are given.

4.1 The concept of hybrid energy system modeling

Cost-effective mitigation strategies minimize total costs of meeting decarbonization targets. However, to assess the impacts of a climate policy, it is necessary to establish the 'boundary' at which the impacts are to be calculated (Söderholm, 2012). A climate policy directly affects the energy sector by requiring additional investments in cleaner technologies and fuels to decarbonize this sector. Based on the distinction given by IPCC (1996), the incurred costs in the energy sector to meet a climate policy target can be divided into "direct engineering and financial cost of a specific technical measure" (e.g., the cost of improving the thermal efficiency of existing buildings) and "economic costs for a given sector" (e.g., the total costs of decarbonizing the power sector). However, policy makers and negotiators need other valuable information concerning the effects that a policy has on the whole economy. In other words, a deep assessment of a mitigation pathway not only addresses the direct impacts on the energy sector, but also takes into account the indirect effects on economic decisions in the remaining sectors of the economy. For a better understanding, consider the case where a CO_2 reduction policy is implemented. The fossil fuel industries will directly suffer from the policy. For instance, some oil refineries have to shut down or at least produce less, which causes negative impacts on the labor income from such facilities, as well as the other related companies. Such impacts, which cannot be addressed within the boundary of the energy sector but may still be significant relative to direct impacts, are referred to as general equilibrium costs.

From the modeling perspective, bottom-up models (e.g., TIAM), which are partial equilibrium representations of the energy sector, are only able to address the direct compliance costs that incur within the energy system. Therefore, despite the significant role of the general equilibrium costs in shaping the political and scientific debates over climate mitigation strategies (Walz and Schleich, 2009), bottom-up models tend to ignore them. According to Blesl and Remme, (2005), by neglecting macroeconomic cost components, bottom-up models tend to underestimate the overall mitigation costs.

The other limitation of bottom-up models, which arises from the partial equilibrium condition, is concerning the fact that demand of energy-services in bottom-up models does not react to rising energy prices (caused by emissions reduction policies). Grübler et al. (2002; P. 336) pointed out that "bottom-up models typically seek to minimize the costs of serving an (often) exogenous energy demand by choosing which technologies to install". As previously discussed, this restricts the flexibility of the model in the context of climate change mitigation, because one important mitigation measure (i.e., price-induced energy-service demand reduction) is disregarded. Hence, relying on bottom-up models cannot offer adequate insights into the development of the energy system toward a decarbonization target.

Moreover, since energy-service demands are given exogenously, bottom-up models are often criticized for not taking into account 'rebound effects' that can influence the effectiveness of energy policies. The rebound effect refers to the idea that the expected reductions in energy consumption, caused by energy efficiency improvements, may be offset partly or completely by an increasing demand for energy services, encouraged by reductions in the effective price of the services resulting from those improvements (Barker et al., 2009). According to Khazzoom-Brookes postulate, it might even happen that improvements in energy efficiency lead to an increase rather than a decrease in energy consumption (Saunders, 1992).

Literature offers different classifications for rebound effects. From one point of view, rebound effects can be divided into two groups: direct rebound effects, and indirect rebound effects. A direct rebound effect arises when improvements in energy efficiency lead to increases in energy service demand (Gillingham et al., 2014). For example, in the manufacturing sector, promoting energy efficiency encourages the substitution of energy for labor or other production factors (Hammond and Norman, 2012). In contrast, the indirect rebound effect refers to the increase in energy consumption from changes in the consumption of other goods and services. For instance, the cost savings from energy efficiency improvements may be reinvested in additional equipment that require energy to produce. The sum of direct and indirect rebound effects represents the economy-wide rebound effect (Sorrell 2007).

From a different perspective, the direct and indirect rebound effects theoretically encompass substitution, income (for households) and output (for producers) effects. According to Chitnis et al. (2012), by making an energy-service cheaper, energy efficiency improvements expand the budget of households/producers, thereby leading to a higher level of utility/output through an increase in consumption/production of other goods and services. This is termed the income/output effect. On the other hand, at a constant level of utility/output, households/producers may substitute the now cheaper energy-service for the consumption of other goods and services. This is referred to as substitution effect. While, the direct rebound effect addresses the net result of the income/output and substitution effects for the relevant energy service, the indirect rebound effect represents the net result of these effects for all the other goods and services (Chitnis et al., 2012). Apart from the described indirect rebound effects, some studies (e.g., Sorrell 2007) additionally have taken into account the energy that is used to produce the required equipment for improving energy efficiency (denoted as embodied energy). However, the most common definition of the indirect rebound effects identifies only the income/output effects (Gillingham et al., 2014). Figure 4-1 illustrates a general classification of rebound effects from energy efficiency improvements and impacts on actual energy savings. As depicted, only part of the calculated energy savings by bottom-up energy models is realized as the actual energy savings.

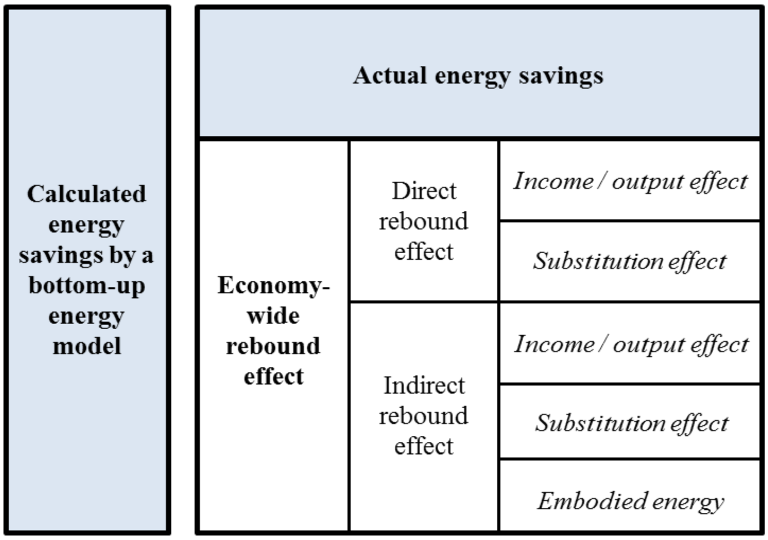


Figure 4-1: Classification of rebound effects and impacts on energy savings – Based on Sorrell (2007, P.4); Chitnis et al. (2012); Chan and Gillingham (2015)

In contrast to bottom-up models, top-down models represent the energy system from an economy-wide perspective. Basically, conventional top-down models rely on analysis of historical trends and relationships to depict large-scale interactions between the energy system and the economy as a whole (IPCC, 1995). They, typically, have a high level of aggregation to examine general equilibrium framework by representing how producers use input factors (e.g., capital and energy) to provide goods and services for households. A big advantage of top-down models is that they considers the linkages between the energy sector and the whole economy in an economically meaningful and consistent way (Söderholm, 2012). This can be of great importance when analyzing the economy-wide impacts of decarbonization policies. In fact, top-down models are able to investigate the economy-wide impacts of climate policies on the level of GDP and its components (household consumption, income, investment, etc.), as well as welfare costs (Andersen and Termansen, 2013; IPCC, 1996).

However, top-down models incorporate relatively little detail on energy system and its components. In essence, they often contain a production function where energy technologies are implicitly characterized by a representative term and energy can be substituted by other production input factors. According to Jaccard et al. (2003), since top-down models are to a large extent based on historical data, they reflect a relatively low willingness to substitute away from fossil fuels. As a result, they are more pessimistic about the potential for CO_2 emission reductions and generate relatively higher mitigation costs (IPCC, 1995). Table 4-1 summarizes general characteristics of top-down and bottom-up models.

Table 4-1: Principal features of bottom-up and top-down modeling approaches – Based on Van Beeck (1999) and Laha and Chakraborty (2017)

Bottom-up models	**Top-down models**
Use an "optimization approach"	Use a "market equilibrium approach"
Represent a detailed description of technologies	Represent high sectoral aggregation
Assess technology and fuel mix within the energy sector	Endogenize representation of behavioral relationships
Do not consider observed market behavior	Are based on observed market behavior
Represent optimistic estimates on "best" performance	Represent pessimistic estimates on "best" performance
Neglect interactions between the energy sector and the other sectors of the economy	Assume there are not discontinuities in historical trends
Ignore the interactions between energy demands and their prices.	Determine energy demand through different economic indices (e.g. price elasticities)
Do not consider rebound effects	Consider rebound effects (partly or completely)

According to Table 4-1, none of the modeling approaches can singly provide all the answers needed. Given the general strengths and weaknesses of top-down and bottom-up models, it can be concluded that they have a complementary perspective about policy analysis. According to Sue Wing (2008; P.548), "the disparities in the structure and scope of bottom-up and top-down models imply that each has a comparative advantage in addressing complementary subsets of the research questions which arise in energy and climate policy analysis".

Hence, an ideal situation for analyzing mitigation pathways is to have a model that includes the detailed technological representation of the bottom-up modeling and simultaneously benefits from economy-wide perspective of the top-down modeling approach. According to Jaccard et al. (2003), such an ideal model should meet three main criteria:

i. Technological explicitness. It refers to the fact that energy models for policy assessment require a detailed representation of energy technologies, including their technical, environmental, and economic specifications.
ii. Microeconomic realism. It presents how decision-makers of firms and households will behave to maximize profits and utilities, considering future advanced technology options.
iii. Macroeconomic completeness. It reflects how changes in the energy sector and energy prices (caused by e.g., a climate policy) influence the structure and output of the entire economy.

Figure 4-2 illustrates the characteristics of conventional top-down and bottom-up models in terms of the aforementioned three key attributes. As depicted, an ideal model scores high on all of the criteria.

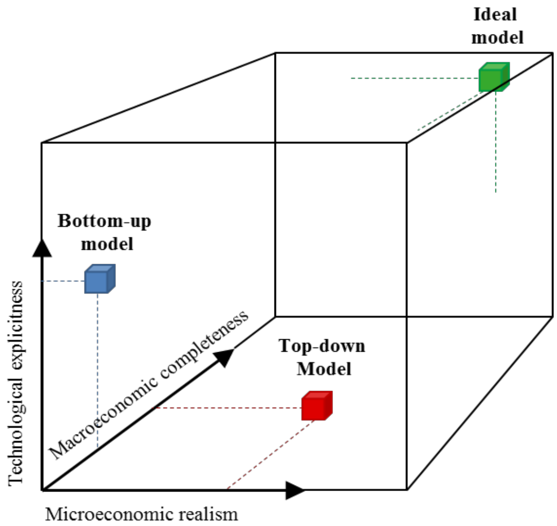


Figure 4-2: Three-dimensional assessment of energy-economy modeling approaches – Based on Jaccard et al. (2003)

A number of attempts have been made to combine top-down and bottom-up models into a single so-called 'hybrid model'. An appropriate hybrid model can generate a wide range of mutually consistent detailed results and high-level macroeconomic results (Tuladhar et al., 2009). As depicted in Figure 4-2, to develop such a hybrid model, the bottom-up and top-down energy-environment models have to move away from their conventional position toward 'ideal model' (Hourcade et al., 2006). In other words, the general strategy is either to increase technological explicitness in a top-down model or to include macroeconomic feedbacks and/or behavioral realism to a bottom-up model.

However, due to some barriers such as different mathematical programming approaches that the top-down and bottom-up models may possess (e.g., linear programming vs. non-linear programming), combining these models can be challenging. Böhringer and Rutherford (2005) identified three general strategies to merge top-down and bottom-up models. First, some modelers use 'soft-linking' approach to link (independently developed) bottom-up and top-down models (see e.g., Krook Riekkola et al., 2013). In this case, two models are run separately but they exchange their main drivers in an iterative manner. Due to its flexibility and transparency, soft-linking is considered as a good starting point in coupling top-down and bottom-up approaches (Martinsen, 2011). However, as Böhringer and Rutherford (2005) pointed out, since top-down and bottom-up approaches have different theoretical assumptions, the soft-linking approach may face issues concerning inconsistency.

A second attempt to merge models is 'hard-linking' which is referred to as coupling one of the model types – either bottom-up or top-down – with a reduced form of the other and solves the resulting (integrated) model in a simultaneous optimization. By hard-linking we mean that all the required information processing and data exchange between the two models are handled without any user judgment by the computer programs (Helgesen, 2013). In contrast to soft-linking, this approach ensures high level of consistency. However, due to the inclusion of a simplified form of one of the models, it represents some aspects in a relatively superficial manner. One of the very first examples of hard-linking of energy-economy models is ETA-MACRO (Manne, 1977) that represents both the energy sector and its inter-linkages with the rest of the economy by a small number of equations.

In the third approach, both model types are directly and fully combined into an integrated model based on developments of solution algorithms for mixed complementarity problem (MCP) (see: e.g., Rutherford, 1995). Although this approach is coherent, flexible, and logical (Böhringer and Rutherford, 2005), due to dimensionality and computational complexities, its implementation is quite challenging. Table 4-2 presents the major benefits and challenges of the described linking approaches.

Table 4-2: Main benefits and challenges of three linking approaches of bottom-up and top-down models

Linking approach	Main benefit(s)	Main challenge(s)
Soft-linking	Flexibility	Inconsistency
Hard-linking	Consistency	Superficiality
Full integration	Flexibility and consistency	Dimensionality and computational complexity

Since the current study mainly focuses on the required energy system transformations, it does not need to cover the interrelationships between the energy sector and the entire economy in a detailed manner. Therefore, it employs the hard-linking approach to couple the TIAM model with MACRO as a top-down, one-sectoral general equilibrium model. The rest of this chapter presents a general description of the MACRO model and elaborates how this model is merged with the TIAM model.

4.2 General description of the MACRO model

The Arrow-Debreu theorem (Arrow and Debreu, 1954) divides the economic system into two general agents: consumers who are demanding goods, and producers who are supplying goods. The theorem assumes that the market is perfectly competitive in the sense that prices are set by market interactions and each agent takes the prices independent of his own choices. Each consumer seeks to maximize its utility and each producer acts to maximize its profit. Under certain conditions (e.g., convex preferences and perfect competition), the theorem states that there must be a set of prices such that supply and demand quantities are in equilibrium on every market and all the agents are fully and individually satisfied.

Computable general equilibrium (CGE) models combine this perspective together with economic assumptions and data to find the supply, demand, and price levels that come to an equilibrium in a set of specified markets (Wing, 2004). The resulting mathematical programming problems are solved by operation research techniques and their results are used to examine policy instruments and market-related institutional characteristics. Notwithstanding, many economists and policy analysts criticize CGE models to be perceived as a "black-box" by non-expert users/readers (Böhringer et al., 2003). Such criticism typically relies on the fact that these models usually contain a large number of equations, variables and parameters which make the overall structure quite complex. As a consequence, understanding the results of a CGE model is often quite challenging and requires specialized techniques.

However, according to Capros et al. (1997), it can be demonstrated that the Arrow-Debreu equilibrium theorem can also be obtained by global (economy-wide) optimization models that implement Pareto optimality (a state of resource allocation in which no one can get better off without making at least one individual worse off) and use equilibrium characteristics introduced by Negishi (1960). Hence, optimization and computable equilibrium models are equivalent. Despite the challenges associated with the application of optimization equilibrium models, the number of such models is increasing. Several attempts have linked different bottom-up energy-system models with the so-called macroeconomic model MACRO.

The MACRO model is described as a single-sector, optimal growth, dynamic inter-temporal, general equilibrium model. The equilibrium is modeled by maximization of a national (or regional) utility function of a single representative producer-consumer agent. The utility is defined as a logarithmic function[7] of consumption. Based on the concept of a single representative producer-consumer, there are no tax or subsidy wedges between the marginal costs of consumption and those of production. Similar to the TIAM model, MACRO is a dynamic model in the sense that it assumes the perfect foresight condition to use the look-ahead feature for choices and decisions throughout the entire planning horizon.

The model formulates the annual production of the remaining economy sector outside of the energy sector by an aggregate production function. Capital, labor and energy-service demands are the input factors of the production. Just as with any other attempts to model a complex economic system, there are pros and cons in employing such a simplified representative production function. The main advantage of this particular abstraction is that it establishes a direct link between "a physical process analysis and a standard long-term macroeconomic growth model" (Manne and Wene, 1992; P.4). It is assumed that the production outcome is spent to cover costs of consumption, investment and energy production. Figure 4-3 illustrates that the link between a single-region TIMES model and the MACRO model proceeds in two opposite directions: while the energy system model determines the energy system costs being

[7] The reason of choosing the non-linear logarithmic utility function instead of a linear one is to avoid "bang-bang" solutions (Remme and Blesl, 2006)

input to MACRO model, the MACRO model provides the level of energy-service demands for the TIMES model.

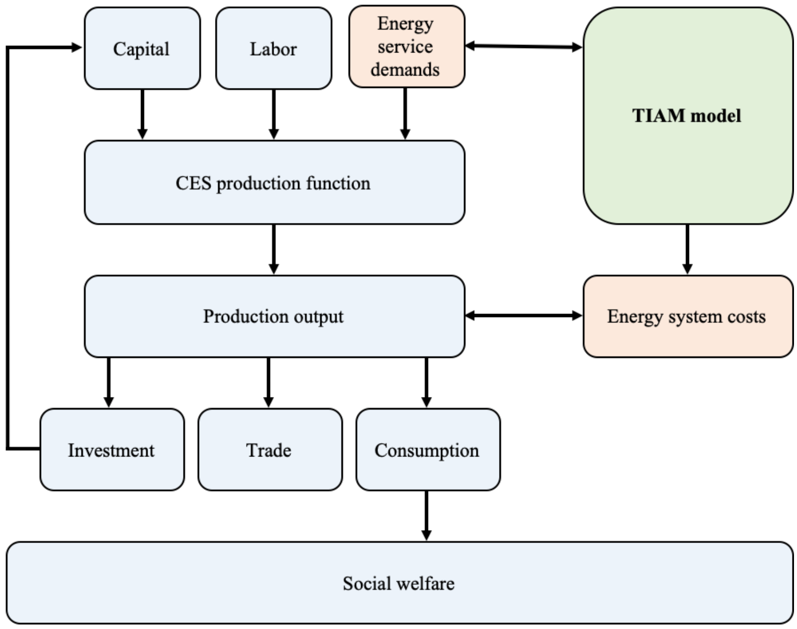


Figure 4-3: The process of linking a single-region TIMES model with the MACRO model

Considering the fact that energy-environmental policies influence energy prices, the MACRO model is capable to address the effect of policies on the whole economy, including possible reallocation of resources that affect the economic growth. Therefore, it provides the possibility to evaluate general macroeconomic implications of such policies. In particular, it enables us to assess the impact of a climate policy in terms of the loss in the GDP, which is normally expressed as a percentage change from a reference case (without the climate policy).

On the other hand, as depicted in Figure 4-3, the model includes an endogenous specification of demand for energy services so as to study the interconnections between energy-service demands and economic development. This enables the assessment of effects of energy-environmental policies on the energy service demands. Consequently, linking MACRO with an energy system model provides the possibility to address the role of energy-service demands in achieving mitigation targets. Moreover, such an endogenous function makes it possible to analyze rebound effects broadly.

The original approach of linking the MACRO model with an energy system model was introduced by Manne (1977) who coupled MACRO with ETA (Energy Technology Assessment model). The successor of ETA-MARCO is MARKAL-MACRO which was developed by Manne and Wene (1992). Later, Messner and Schrattenholzer (2000) merged the MACRO model with a global dynamic system engineering optimization model, MESSAGE (Model of Energy Supply Systems And their General Environmental Impact). Remme and Blesl (2006) used a similar approach of the MARKAL-MACRO model to combine the MACRO model with the TIMES model. The original approach of TIMES-MACRO was developed for single-region TIMES models.

However, linking energy system models with the MACRO model is not restricted to single-region models. Attempts have been made to integrate the MACRO model with multi-regional energy models, where regions are connected through trade links of different goods and each region seeks to maximize its utility. Notwithstanding, since large-scale non-linear optimization problems are regarded as computationally expensive engineering problems (Cheng et al., 2014), solving such models may evoke computational difficulties. Such difficulties even arisen in solving medium-size, multi-regional, global MARKAL-MACRO model with only five regions (Kanudia et al., 2005).

Hence, the standard approach of linking TIMES models with the MACRO model is only applicable for small-size (usually single-region) models. In other words, applying the standard approach for linking the MACRO model with large-scale multi-regional TIMES models even by using very powerful computers and commercial solvers is either impossible or computationally challenging (Kypreos and Lehtila, 2015).

To circumvent the described problem, two general approaches exist. The first one formulates the model under market equilibrium conditions, and solves it using a cutting plane method based on pseudo monotonicity conditions (Bahn et al., 1997). The second approach considers the model formulated with an aggregated utility function and solves it using a decomposition algorithm to break down the optimization problem into smaller problems that are easier to handle. The latter approach has recently been adapted by Kypreos and Lehtila (2013) to link multi-regional TIMES models with the MACRO model.

4.3 A review of the applications of the MACRO model

As earlier mentioned, the MACRO model has been linked to several energy system models in order to evaluate various energy and environmental policies with respect to their general macroeconomic implications. The applications of the MACRO model in peer-reviewed journal papers, presented here, have benefited from three models: ETA-MACRO, MARKAL-MACRO and MESSAGE-MACRO[8].

To analyze alternative global decarbonization pathways, Manne (1992) employed the ETA-MACRO model. This study calculated the macroeconomic impacts of CO_2 reduction policies in five regions: USA, China, former Union of Soviet Socialist Republics, other OECD[9] nations and rest of the world. With the aid of this model, Shimazaki et al. (2000) investigated effects of reducing both CO_2 and SO_2 emissions on energy economies of China and Japan.

[8] Note that although a number of studies have employed TIMES-MACRO and more particularly TIAM-MACRO, no peer-reviewed journal paper has so far used such models

[9] Organization for Economic Cooperation and Development

Furthermore, Bahn et al. (2011) analyzed global mitigation policies that curb greenhouse gas emissions to levels which prevent climate threshold or tipping points being reached.

On the other hand, several studies have applied the MARKAL-MACRO model. Bahn et al. (1997) analyzed the co-operation of three European countries (the Netherlands, Sweden and Switzerland) to curb their CO_2 emissions by 20% through a market of emission permits, using multi-regional MARKAL-MACRO model. Morris et al. (2002) compared the United States version of the model with the National Energy Modeling System (NEMS) model and found both models equally useful to the energy policy analyst. Further, Chen (2005) generated China's scenarios for future energy development and mitigation targets through the year 2050. For the same region, Chen et al., (2007) analyzed the energy transformations toward a low-carbon economy and the associated marginal abatement costs, using MARKAL, MARKAL-ED (MARKAL with elastic demand), and MARKAL-MACRO. In addition, Contaldi et al. (2007) applying the Italian version of the model, evaluated the overall effects of the present Italian Renewable Energy Supply of Electricity (RES-E) obligation. Ko et al. (2010) used this hybrid model to analyze a series of CO_2 emissions abatement scenarios of the power sector in Taiwan.

The applications of the MESSAGE-MACRO model have been made at the global scale. Barreto et al. (2003) employed this hybrid model to discuss the role of hydrogen in transition toward a low-carbon and sustainable global energy system. Riahi et al. (2004) incorporating the learning curve into the energy-modeling framework of this model, examined potentials of CCS technologies based on alternative assumptions for technological progress of CCS. Employing the same approach, Klaassen and Riahi (2007) analyzed the global impacts of a policy that internalizes the (non-climate related) external costs of electricity generation. Table 4-3 provides a summary of the presented applications of the MACRO linkage in peer-reviewed journal papers.

Considering the detailed representation of wide variety of mitigation options, the TIAM-MACRO model is a suitable tool for analysis of mitigation strategies. According to Kriegler et al. (2015), the TIAM-MACRO is considered as a model that is "highly responsive" to climate change. The first application of the full-scale TIAM-MACRO in the field of climate change mitigation was presented by Mousavi and Blesl (2014) in the 66^{th} semi-annual ETSAP meeting. The next section describes the main segments of the TIAM-MACRO model. However, for a detailed description of this model, please see Kypreos and Lehtila (2015).

Table 4-3: A summary of studies that used MACRO in combination with bottom-up models

Model	Author(s), year	Regional focus
ETA-MACRO	Manne (1977)	Global
	Shimazaki et al. (2000)	China and Japan
	Bahn et al. (2011)	Global
MARKAL-MACRO	Bahn et al. (1997)	Netherlands, Sweden and Switzerland
	Morris et al. (2002)	United States
	Chen (2005)	China
	Chen et al. (2007)	China
	Contaldi et al. (2007)	Italy
	Ko et al. (2010)	Taiwan
MESSAGE-MACRO	Barreto et al. (2003)	Global
	Riahi et al. (2004)	Global
	Klaassen and Riahi (2007)	Global

4.4 General structure of the TIAM-MACRO model

TIAM-MACRO can be described as an energy-economy integrated assessment model with a detailed representation of the energy sector. In its broader concept, integrated assessment modeling captures scientific and socio-economic aspects of climate change in a quantitative framework, primarily for the purpose of assessing different policy options that aim to control climate change (Kelly and Kolstad, 2000). A comprehensive review of developments in the field of integrated assessment modeling is given by Ortiz and Markandya (2009).

As aforementioned, to solve the TIAM-MACRO model a decomposition algorithm is adapted. This algorithm breaks down the model into the linear energy system model, TIAM, and a non-linear macroeconomic model called TIAM-MACRO Stand-alone (TMSA). In essence, TMSA is a generalized form of the original MACRO, which supports multiple regions and includes trades between the regions. While trade in all commodities of the energy system is defined in the TIAM model, the TMSA model explicitly includes the trade in monetary unit (numéraire good).

A key function of the TMSA is the economy-wide, aggregate, constant elasticity of substitution (CES) production function representing the annual production of the industry sectors outside the energy system. According to Su et al., (2012), the CES production function is an effective approach to describe the economic behavioral in the sense of resource distribution among several input factors. The original CES production function, originally developed by Arrow et al. (1961), adopts labor and capital as two production inputs (Eq. 4-1).

$$Y_t = F(K_t, L_t) = EF\left[\pi\, K_t^{\frac{\sigma-1}{\sigma}} + (1-\pi)\, L_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \qquad \text{Eq. 4-1}$$

Where,

Y_t	total production in period *t*
K_t	total capital in period *t*
L_t	total labor in period *t*
π	distribution parameter
EF	efficiency parameter
σ	elasticity of substitution parameter

As special cases, the Eq. 4-1 collapses to a Leontief function with fix factor proportion when $\sigma = 0$; a Cobb-Douglas (CD) function when $\sigma \rightarrow 1$; and a linear production function with perfect factor substitution when $\sigma = \infty$.

However, neo-classical aggregate production functions with capital and labor inputs does not explicitly consider energy as a factor of production. In other words, they consider energy as an intermediate product of the defined production factors, rather than a primary input (BrockWay et al., 2017). Notwithstanding, from the early 1970s, economists have routinely included energy as a production input (Sorrell, 2015). Modern economic historians and scientists believe that energy is a vital factor for economic growth (Wrigley, 2010) and therefore it must be seen as a separate production input. As a result, including energy input factor in CES production functions has risen tremendously. From the modeling perspective, "increasing attention on the energy and environmental issues has evoked a revival of the relevant macroeconomic modeling" (Zha and Zhou, 2014; P.793).

In order to include other production input factors such as energy in a CES production function, Sato (1967) generalized the original function by nesting it at two different levels. Most of the studies in the context of energy-economy are based on two-level CES production functions. It is noteworthy that besides energy some studies also consider material as an additional production input factor. According to Antimiani et al., (2015), KLE (Capital-Labor-Energy) and KLEM (Capital-Labor-Energy-Materials) are two general structures which have mostly been used in the literature. The former structure assumes materials as separable from the other factors (Costantini and Paglialunga, 2014). Reviewed studies in a meta-analysis conducted by Koetse et al. (2008), showed that excluding materials factor does not produce any systematic problem.

One of the important properties of a production function is the assumed nesting structure of the input factors. This property reflects the modeler's view about the elasticity between different input factors (Lecca et al. 2011). Over time, numerous studies estimated the goodness of fit of different nesting structures for energy, capital, and labor input factors. Most of these studies highlighted that capital and labor form a composite input, trading off against energy. van der Werf (2008), for instance, using the industry-level statistical data from 12 OECD countries, discussed the integrity of (K-L)-E, (K-E)-L, and (L-E)-K and found the (K-L)-E structure to be the most suited one. While, some macroeconomic models use the (K-E)-L structure (see e.g., Truong, 2007), the majority of such models adopt the (K-L)-E approach. Examples include the DEMETER model (Gerlagh and van der Zwaan, 2003), WITCH model (Bosetti et al., 2007), the EPPA model (Paltsev et al., 2005) and the MERGE model (Manne et al., 1995). More interestingly, all these models apply CD function for the K-L aggregate, which is in line with the historical observations (Hassler et al. 2012).

Accordingly, the (K-L)-E nesting structure with the CD function for capital and labor, has been chosen for the TMSA model. However, considering the structure of the TIAM model, the term energy here refers to energy-service demands. As depicted in Figure 4-4, the production function of TMSA is a nested CES function between the value-added pairs capital and labor and the energy-service demands. The capital-labor composite can be substituted by the demand for energy-services, when their relative prices change. Equation 4-2 presents the mathematical formulation of the production function in TMSA.

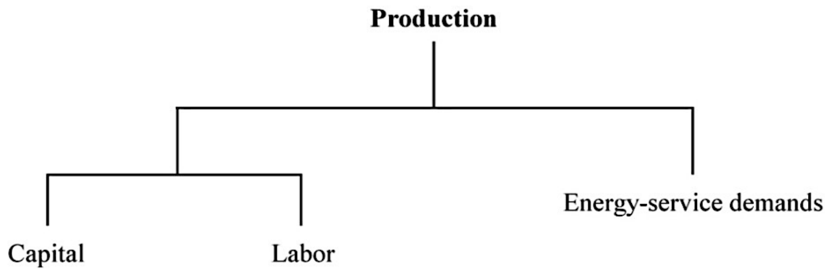


Figure 4-4: Nesting structure of the CES production function in TMSA

$$Y_{r,t} = \left[a_r \, (K_{r,t}^{kpvs_r} \cdot L_{r,t}^{(1-kpvs_r)})^{\rho} + \sum_i b_{r,i} \cdot DM_{r,t,i}^{\rho} \right]^{1/\rho} \quad \text{Eq. 4-2}$$

$$\rho = 1 - 1/\sigma \quad \text{Eq. 4-3}$$

Where,

$Y_{r,t}$	annual production of region *r* in period *t*
$K_{r,t}$	annual capital of region *r* in period *t*
$L_{r,t}$	annual labor growth index of region *r* in period *t*
$DM_{r,t,i}$	annual energy-service demand in MACRO for commodity *i* of region *r* in period *t*
a_r	capital-labor constant for region *r*
$b_{r,i}$	energy-service demand constant for commodity *i* in region *r*
$kpvs_r$	share of capital in the value-added aggregate of region *r*
ρ	substitution constant
σ	elasticity of substitution

The a_r and $b_{r,i}$ constants are determined by a base-year benchmarking procedure based on the results of a stand-alone TIAM model run, using the first-order optimality condition.

According to Cantore and Levine (2011), the constancy of these parameters is a reasonable assumption for such a model.

Besides the nesting structure, another important specification of the production function is elasticity of substitution which is a dimensionless measure, representing the degree to which energy-service demands can be substituted by the aggregate capital-labor, as their relative prices change. For a production function with capital-labor and energy-service demand input factors the elasticity of substitution has the general form of Eq. 4-4.

$$\sigma = \frac{\partial\left(\frac{A_{KL}}{DM}\right)/\frac{A_{KL}}{DM}}{\partial\left(\frac{P_{KL}}{P_{DM}}\right)\Big/\frac{P_{KL}}{P_{DM}}} = \frac{\partial \ln\left(A_{KL}/_{DM}\right)}{\partial \ln\left(P_{KL}/_{P_{DM}}\right)} \qquad \text{Eq. 4-4}$$

Where

A_{KL}	pair capital-labor
DM	energy-service demand
P_{KL}	price for the production factor of pair capital-labor
P_{DM}	price for the production factor energy-service demand

The objective function of TMSA is maximization of the global welfare. However, to sum the regional utility functions, it is essential to assign appropriate weights to them. Without using weights, it can be proven that the model would recommend an equalization of income across all regions, as a part of their policy recommendations (Stanton, 2011). This is due to the fact that the welfare contribution of an abatement depends on the per capita income of the region where it occurs. A non-weighted objective function allocates income losses to richer regions (where each dollar has relatively smaller impact on welfare).

Negishi (1960) showed that a competitive equilibrium is a maximization point of a social welfare function that combines consumers' utility with weights that are inversely proportional to the marginal utilities of income. These weights that freeze the current distribution of income between world regions are called Negishi-weights. Therefore, the objective function of the TMSA model is maximization of the period-wise[10], Negishi-weighted sum of regional utilities, over the entire time horizon (Eq. 4-5). In this model, the Negishi-weights are initially set to be proportional to the regional GDP share. However, to set the weights appropriately, an iterative approach based on the sequential optimization algorithm of Rutherford (1999), is used.

$$Max\ U = \sum_{t=1}^{T}\sum_{r} nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln\left(C_{r,t}\right) \qquad \text{Eq. 4-5}$$

[10] It represents period-length-dependent weights. The period-weights are all 1 if all period lengths are equal to each other

Where,

nwt_r	Negishi weight of region *r*
pwt_t	period-length multiplier weight for period *t*
$dfact_{r,t}$	utility discount factor of region *r* and period *t*
$C_{r,t}$	annual consumption of region *r* and period *t*
T	end of the time horizon

The annual consumption ($C_{r,t}$) is determined by using aggregate production output, aggregate investment, energy costs and trade in numéraire good (Eq. 4-6).

$$C_{r,t} = Y_{r,t} - INV_{r,t} - EC_{r,t} - NEX(nmr)_{r,t} \qquad \text{Eq. 4-6}$$

Where,

$Y_{r,t}$	annual production of region *r* in period *t*
$EC_{r,t}$	annual energy system cost of region *r* in period *t*
$INV_{r,t}$	annual investment cost of region *r* in period *t*
$NEX(nmr)_{r,t}$	annual net export of numéraire good of region *r* in period *t*

While the trade in all energy products is given in the TIAM model, The TMSA model explicitly considers only the trade of the numéraire good. To calculate the price of traded commodities, one has to take into account that from the global point of view, the value of all trade balance surpluses and deficits at each time period is zero (Eq. 4-7). The dual variable of this constraint determines the price of traded commodities.

$$\sum_r NEX(nmr)_{r,t} = 0 \qquad \text{Eq. 4-7}$$

To establish a linkage between each energy-service demand in the TIAM model and the corresponding variable in the TMSA model, a demand decoupling equation is defined. In fact, an energy-service demand parameter in the TIAM model is replaced by an energy-service demand variable in the TMSA model based on the equation given below:

$$DT_{r,t,i} = \prod_{\tau=1}^{t} (1 - ddf_{r,\tau,i})^{\frac{(d_t + d_{t+1})}{2}} \cdot DM_{r,t,i} \equiv DD_{r,t,i} \cdot DM_{r,t,i} \qquad \text{Eq. 4-8}$$

Where:

$DT_{r,t,i}$	annual energy-service demand in the TIAM model for region *r*, period *t* and commodity *i*
$ddf_{r,t,i}$	demand decoupling factor for region *r*, period *t* and commodity *i*
d_t	duration of period *t* (in years)
$DD_{r,t,i}$	integrated demand decoupling factor for region *r*, period *t* and commodity *i*

As previously mentioned, the TMSA includes only the nonlinear macroeconomic part of the TIAM-MACRO. To include TIAM in the decomposition algorithm, it is replaced by Quadratic Supply-cost Functions (QSFs) for energy-service demands (Eq. 4-9). In essence, the QSFs correlate energy-service demands in TIAM to energy system costs in TMSA. The QSFs allow for small changes around the energy-service demands while seeking for the optimal solution and facilitate the convergence. Kypreos and Lehtila (2015) concluded that this approach approximates the energy system well.

$$EC_{r,t} = qa_{r,t} + \sum_{i} qb_{r,t,i} \cdot (DT_{r,t,i})^2 + amp_{r,t} \quad \text{Eq. 4-9}$$

Where,

$qa_{r,t}$	constant term of the QSFs for region *r* and period *t*
$qb_{r,t,i}$	coefficient of energy-service demands in the QSFs for region *r*, period *t*, and demand commodity type *i*:
$amp_{r,t}$	not included annualized investment cost of residual capacities for region *r* and period *t*

To determine $qa_{r,t}$ and $qb_{r,t,i}$, it has to be considered that the energy system of both models are the same at the end of the iterations. Therefore, the partial derivative of the energy cost $EC_{r,t}$ in respect to an energy demand $DT_{r,t,i}$ is equal to the shadow price of the corresponding demand:

$$\frac{\partial EC_{r,t}}{\partial DT_{r,t,i}} = P_{r,t,i} = 2 \cdot qb_{r,t,i} \cdot DT_{r,t,i} \quad \text{Eq. 4-10}$$

Where

$P_{r,t,i}$	undiscounted marginal price for region *r*, period *t*, and demand type *i*

Therefore:

$$qb_{r,t,i} = \frac{P_{r,t,i}}{2 \cdot DT_{r,t,i}} \quad \text{Eq. 4-11}$$

$$qa_{r,t} = AESC_{r,t} - \sum_{i} qb_{r,t,i} \cdot (DT_{r,t,i})^2 \quad \text{Eq. 4-12}$$

Where,

$AESC_{r,t}$	annual energy system cost for region r and period t in TIAM

In order to make the TIAM model consistent with the given equations, its standard objective function (Eq. 3-1) has to be reformulated to consider period-wise average annual costs and period-specific discount factors. Equation 4-13 presents the revised objective function of the TIAM model.

$$\text{Min NPV} = \sum_{r}\sum_{t} pvf_{r,t} \cdot AESC_{r,t} \qquad \text{Eq. 4-13}$$

Where,

$pvf_{r,t}$ present value factor for region *r* and period *t*

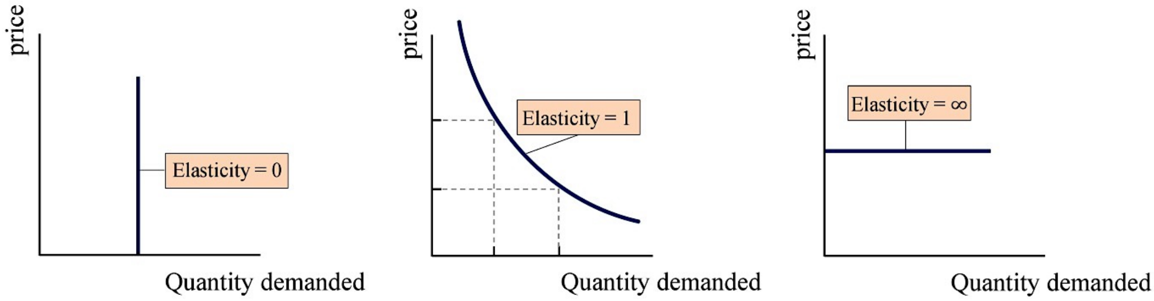
To apply TIAM-MACRO two set of input data are required. The first group contains the input parameters such as the size of the elasticity of substitution. The second group encompasses the initial energy-service demands and GDP projections. The latter input data are essential to calibrate the model. Figure A-1 and Figure A-2 in the Appendix present the steps of applying the TIAM-MACRO model.

5 TIAM-MACRO with variable elasticity of substitution

This chapter presents the methodological novelties of the dissertation, which are a generalization of the TMSA's CES production function to a Variable Elasticity of Substitution (VES) function, and normalization of the production function. The chapter starts by describing the concept of elasticity of substitution and the role of elasticity parameter in the TIAM-MACRO model. In the next step, a detailed background on the VES approach is provided and it is concluded that the VES is a more realistic approach than the other existing approaches. Subsequently, the required changes in the formulation of the TIAM-MACRO model to implement the VES approach are explained. One of these requirements is normalization of the production function, which provides other advantages such as better economic interpretation.

5.1 The concept of elasticity of substitution

In the context of economics, one of the widely-applied concepts is 'price elasticity of demand' representing the responsiveness of the quantity demanded of a commodity to a change in its own price. In fact, it denotes the percentage change in quantity demanded in response to one percent change in the price (holding the other influencing factors constant) (Parkin et al., 2005). Figure 5-1 depicts three demand curves according to the entire range of possible price elasticities. In Figure 5-1 (a), the quantity demanded is constant regardless of the price. In other words, if the price changes but the quantity demanded remains constant, then the price elasticity is zero. In this case, the commodity is said to have a perfectly inelastic demand. As presented in Figure 5-1 (b), if the percentage change in the price equals the percentage change in the quantity demanded, then the price elasticity equals one and the commodity is called to have a unit elastic demand. On the other hand, if a tiny price change leads to a considerable change in the demand of the commodity, then the price elasticity is infinity and the commodity is perfectly elastic. The demand curve in Figure 5-1 (c) shows how the quantity demanded increases regardless of the price.



(a) Perfectly inelastic **(b) Unit inelastic** **(c) Perfectly elastic**

Figure 5-1: Three demand curves according to the entire range of possible price elasticities – Source: Parkin et al. (2005)

It is important to note that the response of a commodity to a change in its price is not restricted to the presented cases. In some cases, the percentage change in the quantity demanded is less than the percentage change in the price. In this condition, the price elasticity is between zero and one and the commodity is said to have inelastic demand. In contrast, if the percentage change in the quantity demanded exceeds the percentage change in the price, then the elasticity value is greater than one and the commodity is said to have an elastic demand.

However, when we extend the notion to a function with more than one variable, the so-called elasticity of substitution parameter appears. The elasticity of substitution is not a novel concept and has been extensively discussed in various areas of economics. This concept was introduced as a "measure of the ease with which the varying factor can be substituted for others" (Hicks, 1932, P. 117). A special class of production functions is those for which the elasticity of substitution is constant. According to Flatau (2002), the elasticity of substitution plays a substantial role in such CES production functions. In fact, the construction of the original CES production function started from the formal definition of the elasticity of substitution (Klump et al., 2011).

Over time, numerous definitions of the elasticity of substitution in the field of macroeconomics have been presented. Adapted from Costantini and Paglialunga (2014), it can be defined as the response of an economy to replace one input factor with another as their relative prices change. Therefore, the higher value of the elasticity parameter, the stronger the changing effect will be. Put another way, this parameter pictures the role of an input factor in production processes by reflecting the degree to which it can be replaced by other input factor(s). Figure 5-2 presents three special cases of degree of substitutability between two commodities. Part (a) depicts the isoquant[11] curves for two ordinary commodities. To consume less of commodity A and remain at the same production level, it is necessary to consume more of commodity B. In contrast, the demand of commodity B increases to compensate for a reduction in commodity A. Part (b) presents the isoquant curves for two perfect substitutes. In this case, commodities can be replaced at a fixed rate. Finally, part (c) shows two perfect complements that cannot be substituted for each other at all.

[11] Isoquant is a curve that represents all the combinations of inputs that yield the same level of production

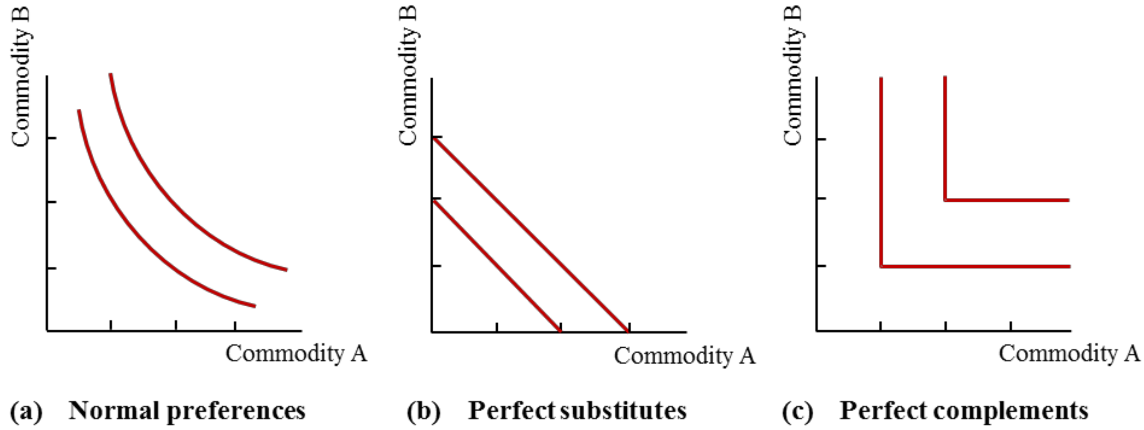


Figure 5-2: Three different types of isoquant curves – Source: Parkin et al. (2005)

5.2 Elasticity of substitution in the TIAM-MACRO model

In the presence of a climate change mitigation policy, next to investing in cleaner technologies, economies allow production firms to react to energy price changes, caused by climate policy, through substitution of input factors. van der Werf (2007) pointed out that a comprehensive analysis of the long run impacts of climate policies requires consideration of substitution of energy with another production factor(s) (e.g., capital). In this case, the elasticity of substitution represents the degree of 'flexibility' in responding to energy price shocks (caused by climate policies): the lower the magnitude of this parameter, ceteris paribus, the less possibility of substitution and therefore the higher will be the required abatement costs to meet the decarbonization targets.

In principle, this parameter is surrounded by uncertainty and can assume any positive value. To provide a reasonable estimation of the elasticity of substitution in the TIAM-MACRO model, it is of great importance to discuss the background of this parameter in empirical studies and also in other similar macroeconomic models.

A large strand of literature has tried to estimate the magnitude of the elasticity of substitution between capital-labor and energy[12], using different sets of empirical data and methodological approaches. A number of studies employed the CES production function with KL-E nesting structure. Using this approach, Chang (1994) estimated the substitution elasticity by 0.42 for manufacturing in Taiwan from 1956 to 1971. For a database of the entire German industry from 1960 to 1993, Kemfert (1998) estimated it by 0.46. Furthermore, van der Werf (2007) employing a cost-function-based approach, investigated the industry sector of 12 OECD countries from 1978 to 1996. According to the results of this study the substitution elasticity varies between 0.17 to 0.62, depending on the combination of countries and industry branches. Using the same technique, Okagawa and Ban (2008) analyzed the substitution elasticities for

[12] Mostly refers to final energy consumption

19 industries in 14 countries from 1990 to 2004. They highlighted that energy-intensive industries have relatively higher values of the substitution elasticity. On the other hand, Su et al. (2012) dealt with an aggregate production function with capital, labor and energy inputs for China in the period of 1953 to 2006 (including the market period from 1979 to 1996). They divided the time period into three periods and for each they found a specific elasticity of substitution. Accordingly, the highest elasticity of substitution was estimated by 0.76 for the market period. Interestingly, Shen and Whalley (2013) determined China's elasticity of substitution for the same market period but came to the value of 0.69. This confirms that the estimation of elasticity not only depends on the selected database but also relies on the chosen methodology. Table 5-1 presents a summary of the reviewed empirical studies.

Table 5-1: Review of empirical estimations of elasticity of substitution between capital-labor and energy

Authors	Data	Estimate
Chang (1994)	Taiwanese manufacturing 1956-1971	0.42
Kemfert (1998)	German Industry 1960-1993	0.46
Kemfert and Welsch (2000)	German Industry 1970-1988	0.70
van der Werf (2007)	12 OECD Manufacturing 1978-1996	0.17-0.62
Okagawa and Ban (2008)	14 OECD Manufacturing 1995-2004	0-0.64
Su et al. (2012)	China 1953-1978	0.28
	China 1953-2006	0.4
	China 1979-2006	0.76
Shen and Whalley (2013)	China 1979-2006	0.69

Referring to the Table 5-1, there is a great deal of empirical evidence that aggregate production function with (K-L)-E nesting structure is better characterized by an elasticity of substitution (between Capital-Labor and Energy) below unitary rather than unitary or above unitary. However, as aforementioned, the empirical estimates are open to the criticism that they vary not only according to the databases but also with regard to the selected estimation methodology. Furthermore, they are restricted to certain regions. Hence, without further investigations, it is not practical to directly apply any of them to a macroeconomic model. In fact, to determine the accompanying substitution elasticities, modelers not only are inspired by the empirical estimations but also have to consider specifications of their models. Table 5-2 presents an overview of the elasticity of substitutions between the pair Capital-Labor and Energy ($\sigma_{(K-L)-E}$) in existing macroeconomic models.

To provide a reasonable estimate for the elasticity of substitution in the TIAM-MACRO model, one may think of borrowing the conventional values used in the given models. Table 5-2 presents the assumed values for elasticity of substitution between capital-labor and energy in five macroeconomic models. It is seen that while four models assume it to be 0.4, the WITCH model takes 0.5. However, the major problem of this approach is that in the given models the term energy is referred to as final energy consumption, while in the TIAM-MACRO model it represents the aggregated energy-service demands. Due to the fact that final energy consumption can be reduced not only by decreasing energy-service demands but also through using more efficient end-use technologies, assuming the conventional values for the elasticity of substitution in the TIAM-MACRO model may overestimate the combined demand response. Therefore, it can be argued that 0.5 (as the maximum estimate in Table 5-2) can be served as an upper-bound for the elasticity parameter in the TIAM-MACRO model.

Table 5-2: Assumed values for the elasticity of substitution between capital-labor and energy in macroeconomic models

Study	**Model**	$\boldsymbol{\sigma_{(K-L)-E}}$
Alan and Richard (1992)	Global 2100	0.4
Manne et al. (1995)	MERGE	0.4
Gerlagh and van der Zwaan (2003)	DEMETER	0.4
Paltsev et al. (2005)	EPPA	0.4
Bosetti et al. (2007)	WITCH	0.5

The study that particularly dealt with the size of the elasticity of substitution in TIMES-family models was conducted by Läge (2001). He found the range of 0.2 to 0.5 to be reasonable for such models. Loulou et al. (2004) discussed that for the energy system models with a detailed representation of the end-use sectors and several saving options, the elasticity of substitution should be in the lower range to avoid double counting, while for the models having a limited representation of the end-use technologies, the elasticity of substitution should get a larger value. To provide a 'best guess' estimate, a sensitivity analysis regarding this parameter has been previously conducted. As a result, in the standard TIAM-MACRO model, the elasticity of substitution is assumed to be 0.25 (Remme and Blesl, 2006).

On the other hand, TIAM-MACRO assumes that the elasticity of substitution is constant across the model regions and over the time horizon. Under this assumption, all regions in the model react similarly to a unit change of the relative prices of the production inputs. Furthermore, the assumption represents that the behavior of economies does not change over time. Considering the long-term horizon of the model, one can argue that as time passes, economies may react differently to a unit change in relative prices of the production inputs. Although the standard version of the model can take regionally different elasticities, it is not able to have time-dependent elasticities. Hence, for a deeper analysis of climate policies, it is important to generalize the production function of the MACRO model in a way that it allows the elasticity of substitution to vary across regions and over time.

5.3 Variable elasticity of substitution

In the standard neoclassical growth literature, as well as in business-cycle analysis, typically, production of firms has been expressed mainly by the CD aggregate production function (Hassler et al., 2012). This is primarily due to the simple and straightforward structure of this production function form. Notwithstanding, empirical evidence shows that the value of the elasticity of substitution is not necessarily restricted to unity, meaning that the inputs can be substituted for each other in varying degrees (Lu, 1967). To overcome this "significant constraint" (BrockWay et al., 2017; P.2), the CES production function form was developed by Solow (1956).

Despite the advantages of the CES production function, similar to the CD function, it is subject to the constancy of the elasticity of substitution (but not necessarily unity). Generally speaking, the constancy of the elasticity of substitution implies that the reaction of an economy to substitute production inputs remains unchanged. In other words, this assumption represents a unique and fixed functional from for the production function over time. This, however, seems to be a simplifying assumption that does not fit the reality. In other words, it should be possible that the elasticity of substitution varies. As clearly stressed by Schefold (2008, P.791) "we see no obvious reason why the elasticity of substitution should be constant". Hence, it is desirable to develop a more general and flexible production function that permits the elasticity of substitution to vary over time. The new so-called Variable Elasticity of Substitution (VES) production function or homothetic production function was formally introduced by Revankar (1971a). According to Kazi, (1980), the VES function can address possible specification biases in the CES and CD functions.

Once the assumption of constancy is dropped and the variability of the substitution elasticity is admitted, we face a variety of alternatives for its functional form. The resultant production function, therefore, depends on the assumptions involved in the function of elasticity of substitution. Some approaches have previously identified reasonable functions for the elasticity of substitution in capital-labor production functions. Sato and Hoffman (1968) proposed the extent to which one can develop a VES and still derive an explicit form of the production function. One approach relates the elasticity of substitution to the ratio of the production inputs. Sato (1967), for instance, assumed that the elasticity of substitution is a linear function of inputs ratio in a production function with capital and labor inputs. Given the fact that the capital to labor ratio is directly associated with economic growth, the elasticity of substitution in this approach is endogenously linked to the economic growth. According to Miyagiwa and Papageorgiou (2007), it is reasonable to assume that the elasticity of substitution varies according to the level of economic development of a country or region.

On the other hand, another approach defines the elasticity of substitution as a function of time. In contrast to the previous approach, the elasticity of substitution in this approach is exogenously given. The outcome is a production function which may be characterized as a shifting CES function. In other words, the underlying production function is a CES function at any point. For example, Sato and Hoffman (1968) proposed that elasticity of substitution as a positive linear function of time. They basically assumed that as time passes, more opportunities to substitute production input factors become available.

In summary, determining the functional form of elasticity of substitution in a VES production function is mainly derived from our interpretation regarding the elasticity of substitution. This is especially important in the context of macroeconomic modeling where the elasticity of substitution possesses a central position in the economic forecasts and policy (Miller, 2008).

5.3.1 Empirical observations of the variable elasticity of substitution

There exist a large number of empirical studies that have employed the VES production function for production functions with capital and labor inputs. Examples include Lovell (1973) analyzing U.S. manufacturing data over the period of 1929 to 1953, Zellner and Ryu (1998) investigating U.S. transportation equipment industries in the year 1957, Roskamp (1977) examining German manufacturing data over the period 1950 to 1960, and Ramcharran (2001) evaluating the U.S. industry's productivity and efficiency for the period 1976 to 1993. Moreover, there are several studies that have tested the adaptation of this approach compared with the CES and the CD approaches. In this regard, Sato and Hoffman (1968), using the VES and CES approaches for private non-farm sectors of the United States from 1909 to 1960 and Japan from 1930 to 1960, found that the VES is “more realistic” than the other approach. Lovell (1968) rejected both the CD and CES forms in favor of the VES approach for 16 two-digit U.S. manufacturing industries over the period of 1949 to 1963. Moreover, Lu and Fletcher (1968) rejected the CES in favor of the VES for 7 to 9 (depending on definition of production inputs) U.S. two-digit manufacturing sectors. Diwan (1970) analyzed 500 U.S. individual manufacturing firms for the period of 1955 to1957 and found more evidence supporting the VES approach.

In addition, Revankar, (1971a) and Revankar, (1971b) analyzing U.S. manufacturing sectors over the year 1957 and U.S. manufacturing sectors over the period from 1929 to 1953, respectively, highlighted higher empirical relevance of the VES compared to the other forms of production function. Based on an empirical test on U.S. agriculture data, Meyer and Kadiyala (1974) pointed out that the VES is the most suitable approach. Further, Sirmans et al. (1979) investigating the single-family housing data of Santa Clara County, California, shed light on better performance of the VES compared to the CES. Likewise, Kazi (1980) using data on 24 two-digit and three-digit industries of India over the period of 1973-1975, concluded that the VES is a “statistically significant and theoretically relevant argument in production functions”, while the CES contains “specification bias”. Bairam (1989) and Bairam (1991) rejected the CD in favor of the VES approach, utilizing data of the private nonfarm sector of Japan and Soviet economies, respectively. Furthermore, Karagiannis et al. (2005) admitted the validity of the VES production function for a panel data of 82 countries over the period of 1960 to 1987.

Table 5-3 reports the empirical studies that statistically confirmed the VES represents the reality better than the other studied form(s). Reviewing the discussed studies let us conclude that the VES is more realistic than the CD and CES approaches.

Table 5-3: Empirical studies confirming that VES is a more realistic approach compared to the other forms

Study	Data	Rejected form(s) in favor of the VES	
		CD	CES
Lu and Fletcher (1968)	U.S. Two-digit manufacturing (1957)		×
Sato and Hoffman (1968)	U.S. Private non-farm (1909-1960) Japan Private non-farm (1930-1960)		×
Lovell (1968)	U.S. Two-digit manufacturing (1946-1963)	×	×
Diwan (1970)	U.S. Individual manufacturing (1955-1957)	×	×
Revankar (1971 a)	U.S. Two-digit manufacturing (1957)	×	
Revankar, (1971b)	U.S. Manufacturing (1929-1953)	×	
Lovell (1973)	U.S. Manufacturing (1947-1968)	×	×
Meyer and Kadiyala (1974)	U.S. Agriculture	×	×
Sirmans et al. (1979)	California Single-family housing (1940-1963)		×
Kazi (1980)	India Two-digit and three-digit manufacturing (1973-1975)		×
Bairam (1989)	Japan Economy (1878-1939)	×	
Bairam (1991)	Soviet Economy (1950-1975)	×	

5.4 Implementation of the variable elasticity of substitution in TIAM-MACRO

The first step to implement the VES production function in the TIAM-MACRO model is to find a function for the elasticity of substitution. To develop such a function, it is necessary to consider the economic interpretation of the elasticity of substitution in this model. Furthermore, it should be considered that the elasticity of substitution can be given either as an endogenous function (i.e., as a model variable) or as an exogenous function (i.e., as a model parameter). For instance, one may argue that the willingness of an economy to substitute energy-service demands with the capital-labor aggregate depends on the ratio of total energy system costs in the GDP. This suggests that the more the share of total energy system costs in the GDP, the higher is the willingness of the economy to reduce energy-service demands. In this case, the elasticity of substitution is endogenously linked to the GDP and energy system costs variables. Therefore, it is considered as a model variable. In contrast, it can be assumed that the elasticity of substitution is a function of time. In this way, the elasticity of substitution is said to possess an exogenous function and therefore it is served as a model parameter.

This dissertation as the first study that employed the VES approach in an energy-economy model, the degree of elasticity for each time period/region is given to the model as an exogenous parameter. Moreover, due to the fact that the main concern of this study is the evaluation of the mitigation measures, the main analysis of the current study is conducted by using the standard TIAM-MACRO model (with the CES production function). This means that the VES approach is considered as a part of the scenario analysis to identify and highlight the possible impacts of changing the elasticity of substitution on the main results. Hence, in this section, the necessary changes in the TIAM-MACRO formulation to support the VES approach are given. The assumed function for the elasticity of substitution and subsequently the assigned values for each time period/region are presented in chapter 6.

Basically, the implementation of the VES production function requires principal changes in the formulation of the TMSA model. To support time-region dependent elasticity of substitution, the CES production function (given in Eq. 4-2) can be easily generalized to support variable elasticity of substitution (Eq. 5-1). Note that the CES approach is a special case of the VES production function.

$$Y_{r,t} = \left[a_r \cdot K_{r,t}^{kpvs_r \cdot \boldsymbol{\rho_{r,t}}} \cdot L_{r,t}^{(1-kpvs_r) \cdot \boldsymbol{\rho_{r,t}}} + \sum_i b_{r,i} \cdot DM_{r,t,i}^{\boldsymbol{\rho_{r,t}}} \right]^{1/\boldsymbol{\rho_{r,t}}} \quad \text{Eq. 5-1}$$

$$\rho_{r,t} = 1 - 1/\sigma_{r,t} \quad \text{Eq. 5-2}$$

Where,

$\rho_{r,t}$	substitution constant for region *r* in time period *t*
$\sigma_{r,t}$	elasticity of substitution for region *r* in time period *t*

Accordingly, the production function constants should be revised, using the benchmarking process discussed. Equations 5-3 and 5-4 present the new production constants.

$$b_{r,i} = P_{r,0,i} \cdot (\frac{DM_{r,0,i}}{Y_{r,0}})^{1-\rho_{r,0}} \quad \text{Eq. 5-3}$$

$$a_r = \frac{{Y_{r,0}}^{\rho_{r,0}} - \sum_i b_{r,i} \cdot DM_{r,0,i}^{\rho_{r,0}}}{K_{r,0}^{kpvs_r \cdot \rho_{r,0}}} \quad \text{Eq. 5-4}$$

Since the production constants (apart from being dependent on the base-year values of the variables) are dependent on the elasticity of substitution in the first period (ρ_0), running the TIAM-MACRO model with the VES production function is not straightforward. This is due to the fact that changing the elasticity of substitution from one period to the other may change the whole structure of the production function. In practice, when the production function is transformed to the VES form and subsequently the other related adjustments in the source code are applied, a number of errors appear in the calibration process. Hence, the original MACRO model does not allow to implement the VES approach. Therefore, in order to apply the VES approach, it is necessary to define a new production function in a way that the constants become independent from the elasticity of substitution.

The next section presents the normalization of the production function as a solution to the described problem. However, we show that the benefit of the normalization goes beyond the implementation of the VES case and remedies the lack of economic reasoning of the original CES production function. In other words, it is recognized that independent to employing the VES approach, the production function of the TMSA model has to be normalized to avoid conceptual and economic interpretation difficulties.

5.5 Normalization of the production function

The correct, consistent and meaningful use of dimensions is essential for any scientific work that includes mathematics. In essence, a necessary, though not sufficient, condition for an equation to be valid is ‘dimensionally homogeneous’ - i.e., both sides of an equation must have the same units (Prieto and Stefanovskiy, 2003). One of the main critiques against the original form of the CES production function, which has been extensively addressed in the literature (see e.g., De Jong 1967 and De Jong and Kumar, 1972), is associated with the lack of this crucial property. Strictly speaking, it can be shown that the standard CES production where the input factors take different units, is not dimensionally homogeneous (Cantore and Levine, 2011; Kim, 2015).

In particular, the CES production function of the TMSA model suffers from this problem because the production inputs are measured in different units. In this function, capital and production output are defined in a monetary unit, labor index does not have any unit and energy-service demands are measured in [PJ], [Bv-Km] and [Mt]. To have the same unit at both sides of the Eq. 5-1 the production function constants (a_r and $b_{r,i}$) must take units. This, however, appears to contradict with the nature of these constants as they are “share parameters” and should be dimensionless (Cantore and Levine, 2011). According to Barnett (2004), production functions with dimensional constants are either meaningless or economically unreasonable.

On the other hand, since the production function constants depend on the elasticity of substitution, comparative static exercises[13] for such a production function with identical baseline values but different elasticity of substitutions turn out to be quite challenging. Moreover, as discussed in the previous section, such a production function does not allow us to implement the VES approach.

It can be concluded that the original production function of the TIAM-MACRO model contains dimensional constants which are economically meaningless. In addition, as they are dependent to the elasticity of substitution, extending the function to the VES form causes

[13] In economics, comparative statics is the act of comparing two different economic outcomes, before and after changing an exogenous parameter

computational errors and complexities. Therefore, it is necessary to modify this function in a way that (without any significant structural change) the constants become dimensionless and also independent to the elasticity of substitution.

To address these issues, two general approaches have been discussed in the literature: re-parameterization and normalization. While the former approach has been recently applied in few studies (e.g., Cantore and Levine, 2012), the latter approach is at the center of a rapidly increasing literature in empirical and theoretical macroeconomics. Due to its advantages, in this study, the normalization approach is applied.

The concept of explicitly normalizing CES production functions was originally introduced by de La Grandville (1989) and further explored by Klump and de La Grandville (2000). To present how normalization has been uncovered, first the straightforward normalization procedure for CD functions is presented. Consider the general form of the CD function given in the Eq. 5-5.

$$Y_t = M \cdot (K_t)^{\sigma} \cdot (L_t)^{1-\sigma} \qquad \text{Eq. 5-5}$$

Where,

M composite constant

It is obvious that if the input factors and the output take different units, then the constant (M) is dimensional, which depends on the choice of units. Note that, the problem disappears if, for example, capital is the only input ($\sigma = 1$) and it has the same dimension as the production output. In this case, the constant denotes output per unit of capital or capital productivity. To remedy the problem for the general form, De Jong (1967) proposed a simple procedure. According to this procedure, Y_0, K_0 and L_0 , as steady-state baseline values, are defined, which together satisfy the production function. Hence:

$$Y_0 = M \cdot (K_0)^{\sigma}(L_0)^{1-\sigma} \qquad \text{Eq. 5-6}$$

It is clear that dividing Eq. 5-5 and Eq. 5-6 eliminates the constant:

$$\frac{Y_t}{Y_0} = \left(\frac{K_t}{K_0}\right)^{\sigma} \cdot \left(\frac{L_t}{L_0}\right)^{1-\sigma} \qquad \text{Eq. 5-7}$$

In the new functions, Y_t/Y_0 , K_t/K_0 and L_t/L_0 are dimensionless. Therefore, the revised function does not require specifying unit of measures. In other words, the new production function is more economically reasonable.

However, when we move a step further to the CES production function, the approach is not that simple and straightforward. According to Klump et al. (2011), normalization of the CES function starts from the fact that the elasticity of substitution is implicitly defined as a point elasticity, which relates to one particular baseline point on one particular isoquant. The baseline point is regarded as a specific point in time (t_0). Referring to the original definition of the elasticity of substitution which is the percentage change in the ratio of input factors in response to a change in the Marginal Rate of Technical Substitution (MRTS[14]) (Paterson, 2012), it is evident that at this specific point, a family of CES functions with different elasticity of substitutions are characterized by the same input factor proportion and the same MRTS (Figure 5-3). Hence, changing the elasticity of substitution should make the old and the new isoquants tangent and not intersecting at the baseline point. This can be obtained through normalization of the production function.

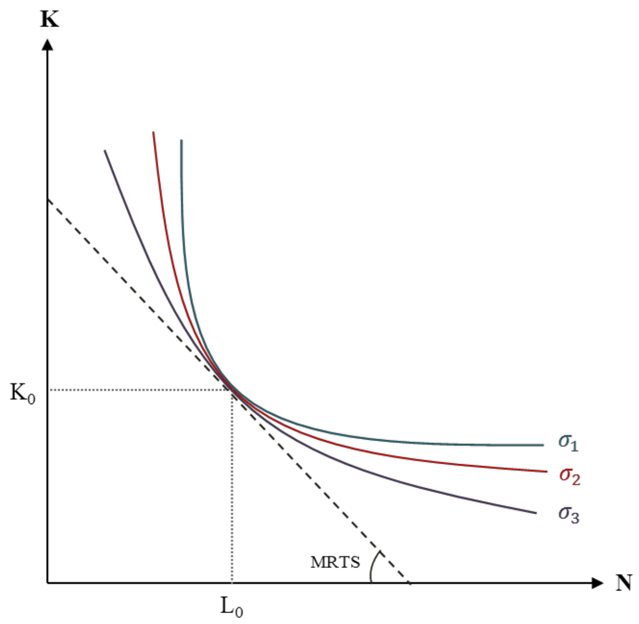


Figure 5-3: Isoquants of a normalized production function with different elasticities

Therefore, it can be argued that the formal construction of the CES production function is intrinsically linked to normalization (Klump et al., 2011). As stated by Leon-Ledesma et al. (2010), normalization guarantees that members of the same CES family are distinguished only by the mean of elasticity of substitution and they share the same fixed benchmark values for the level of production, input factors, and for the MRTS.

The given definition of the elasticity of substitution leads us to the following function:

$$y = \gamma w^{\sigma} \qquad \text{Eq. 5-8}$$

Where

γ integration constant

Under certain conditions (e.g., constant returns to scale), the Eq. 5-8 can be transformed to the form of the following equation:

[14] Denotes the slope of an isoquant

$$y = \gamma(y - k\frac{dy}{dk})^{\sigma} \qquad \text{Eq. 5-9}$$

After simplification and integration of the parameters, the CES production function is obtained:

$$y = (\alpha\, k^{\frac{\sigma-1}{\sigma}} + \beta) \qquad \text{Eq. 5-10}$$

Where α and β are the production constants. It can be shown that the latter constant depends on the elasticity of substitution. To determine these two constants in an economically meaningful way, baseline values (w_0 , y_0 , k_0) are applied to Eq. 5-9 and Eq. 5-10:

$$w_0 = y_0 - k_0 \frac{dy}{dk}\bigg|_{t=t_0} \qquad \text{Eq. 5-11}$$

$$y_0 = (\alpha\, k_0^{\frac{\sigma-1}{\sigma}} + \beta) \qquad \text{Eq. 5-12}$$

Using Eq. 5-10, Eq. 5-11 and Eq. 5-12, the following CES production function can be derived:

$$\frac{y_t}{y_0} = \left[\pi \left(\frac{k_t}{k_0}\right)^{\frac{\sigma-1}{\sigma}} + (1-\pi)\right]^{\frac{\sigma}{\sigma-1}} \qquad \text{Eq. 5-13}$$

Extending this function leads to the standard normalized CES production function:

$$\frac{Y_t}{Y_0} = \left[\pi \left(\frac{K_t}{K_0}\right)^{\frac{\sigma-1}{\sigma}} + (1-\pi)\left(\frac{L_t}{L_0}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \qquad \text{Eq. 5-14}$$

Where,

π the capital share in total production at the baseline point (production constant)

In this function, the production constant (π) equals $\frac{y_0 - w_0}{y_0}$. Hence, it is a dimensionless parameter that does not depend on the elasticity of substitution. This means that the new normalized function gives a more consistent and meaningful economic interpretation. According to Andic (2016), the main advantage of the normalized CES function is that the parameters have a clear empirical correspondence. On the other hand, by holding the structure of the function independent from the elasticity of substitution, the normalization permits us to compare results when the elasticity parameter changes, and therefore avoids "arbitrary comparisons" (Cantore and Levine, 2011 P.5).

The described general advantages of using normalized production functions demonstrate the importance of this approach. However, one particular benefit of the normalization in the TMSA model is concerning the use of the VES approach; it permits one to consider that the elasticity of substitution in the TMSA model may vary over time. After presenting the background of the normalization in the next section, it is explained how this approach is applied to the TMSA model.

5.5.1 Background of the applications of the normalization approach

As earlier mentioned, the explicit normalization approach was introduced in the seminal paper of de La Grandville, (1989), and further explored by Klump and de La Grandville, (2000). Due to the advantages of the normalized CES production function, it has been intensively applied in various theoretical and empirical macroeconomic studies. These studies especially examined the impact of variation in elasticity of substitution on the macro-economy such as steady-state level of macroeconomic variables, the rate of economic growth, and the speed of convergence (Wong and Yip, 2010). In order to emphasize the advantages of the normalized production function over the un-normalized case, a short review of the applications of this approach is provided here.

In the context of growth models, Klump and Preissler (2000) investigated inconsistencies and controversies related to the use of the CES production function. They, for the first time, analyzed the influence of the elasticity of substitution on the speed of convergence. According to this study, the normalized production function can solve the “inter-family” problem of the CES production function. Miyagiwa and Papageorgiou (2003) examined the effect of changing the elasticity of substitution on wages and highlighted the role of the normalization procedure to correct the bias inherent in the use of CES production functions. This conclusion has been later confirmed by Saam (2004) who evaluated the effect of a rise in the elasticity of substitution on distribution of capital and labor. Moreover, Klump and Saam (2008) presenting a particular example on the speed of convergence in the Ramsey model, illustrated how neglecting normalization can lead to biased results and how normalization helps to overcome those biases. On the other hand, Papageorgiou and Saam, (2008), studied the effect of elasticity of substitution on the transitional dynamics in Solow and Diamond growth models. They drew special attention to the importance of the normalization for such models. Later, Wong and Yip, (2010) employed a normalized production function to systematically compare production functions with different elasticity of substitutions. For a similar purpose, Xue and Yip (2012) employed a particular normalization approach which was originally developed by Lansing and Guo (2009).

However, as stated by Leon-Ledesma et al. (2010), besides offering several theoretical advantages, the normalization also provides empirical benefits and helps to overcome the “impossibility theorem” explored by Diamond et al. (1978). Accordingly, several empirical studies (e.g., Klump et al., 2004; Klump et al., 2007; Mallick, 2012; Li and Stewart; 2014; Growiec et al., 2015) benefited from normalized CES production functions. Major findings of these studies confirm that using the normalization, parameters of the production function represent separate concepts, which are otherwise highly intertwined.

5.5.2 Normalization of the production function in the TIAM-MACRO model

To normalize the CES production function of the TIAM-MACRO model, adopting the original approach, all the variables (i.e., the input factors and the output) are divided to their base-year values:

$$Y_{r,t} = Y_{r,0} \cdot \left[a_r^* \cdot (\frac{K_{r,t}}{K_{r,0}})^{kpvs_r.\rho} \cdot L_{r,t}^{(1-kpvs_r).\rho} + \sum_i b_{r,i}^* \cdot (\frac{DM_{r,t,i}}{DM_{r,0,i}})^{\rho} \right]^{1/\rho} \quad \text{Eq. 5-15}$$

Where,

$Y_{r,0}$	annual production of region *r* in the base-year
$K_{r,0}$	annual capital of region *r* in the base-year
$DM_{r,0,i}$	annual energy-service demand of region *r* in the base-year for commodity *i*
a_r^*	capital-labor constant for region *r*
$b_{r,i}^*$	new energy-service demand constant for commodity *i* in region *r*

To benchmark the new production constants, first, it should be noted that the base-year values ($Y_{r,0}$, $K_{r,0}$, $DM_{r,0}$) satisfy the production function. Hence:

$$1 = a_r^* + \sum_i b_{r,i}^* \quad \text{Eq. 5-16}$$

To determine the energy service constants ($b_{r,i}^*$) the first-order optimality condition for the base-year is applied. For this period, the partial derivative of the production function with respect to the energy demands equals the corresponding energy-service prices (Eq. 5-17). The prices denote shadow prices of energy-services in the first period, which are obtained from the stand-alone TIAM model.

$$\left. \frac{\partial Y_{r,t}}{DM_{r,t,i}} \right|_{t=0} = P_{r,0,i} \quad \text{Eq. 5-17}$$

Where,

$P_{r,0,i}$	annual production of region *r* in the base-year

Using this equation, the new service demand constants ($b_{r,i}^*$) are obtained:

$$b_{r,i}^* = P_{r,0,i} \cdot (\frac{DM_{r,0,i}}{Y_{r,0}}) \quad \text{Eq. 5-18}$$

In contrast to the original CES production function, the production constants in the normalized version are dimensionless. Furthermore, they do not depend on the value of elasticity of substitution. Therefore, the new (normalized) CES production function of the TIAM-MACRO model provides more convincing economic interpretation. In addition, it gives the opportunity to implement the VES approach without any barrier. That is to say, the normalized function is more flexible so that it allows the elasticity of substitution of a region to vary over the time horizon. Equation 5-19 presents the normalized nested VES production function of the TIAM-MACRO model.

$$Y_{r,t} = Y_{r,0} \cdot \left[a_r^* \cdot (\frac{K_{r,t}}{K_{r,0}})^{kpvs_r \cdot \rho_{r,t}} \cdot L_{r,t}^{(1-kpvs_r) \cdot \rho_{r,t}} + \sum_i b_{r,i}^* \cdot (\frac{DM_{r,t,i}}{DM_{r,0,i}})^{\rho_{r,t}} \right]^{1/\rho_{r,t}} \quad \text{Eq. 5-19}$$

The adaptation of the new production function requires revising the demand decoupling equation which is recalled here:

$$DT_{r,t,i} = \prod_{\tau=1}^{t} (1 - ddf^*{}_{r,\tau,i})^{\frac{(d_\tau + d_{\tau+1})}{2}} \cdot DM_{r,t,i} \equiv DD_{r,t,i}^* \cdot DM_{r,t,i} \quad \text{Eq. 5-20}$$

Where

$ddf^*{}_{r,t,i}$	new demand decoupling factor for region *r*, period *t* and commodity *i*
$DD^*{}_{r,t,i}$	integrated demand decoupling factor for region *r*, period *t* and commodity *i*

The new decoupling factors are computed in a calibration routine (similar to the original approach), using only the TIAM model. It should be considered that the partial derivative of the production function ($Y_{r,t}$) with respect to an energy demand of the TIAM model ($DT_{r,t,i}$) is equal to the shadow price of the corresponding demand commodity ($P_{r,t,i}$):

$$P_{r,t,i} = \frac{\partial Y_{r,t}}{\partial DT_{r,t,i}} \quad \text{Eq. 5-21}$$

$$\frac{\partial Y_{r,t}}{\partial DT_{r,t,i}} = Y_{r,0} \cdot \frac{b_{r,i}^*}{[DD_{r,t,i}{}^* . DM_{r,0,i}]^{\rho_{r,t}}} \cdot DT_{r,t,i}^{(\rho_{r,t}-1)} \left(\frac{Y_{r,t}}{Y_{r,0}}\right)^{(1-\rho_{r,t})} \quad \text{Eq. 5-22}$$

$$DD_{r,t,i}^* = \left[\frac{Y_{r,0} \cdot b_{r,i}^* . DT_{r,t,i}^{(\rho_{r,t}-1)} \cdot Y_{r,0}^{(\rho_{r,t}-1)}}{P_{r,t,i} \cdot Y_{r,t}^{(\rho_{r,t}-1)} \cdot DM_{r,0,i}^{\rho_{r,t}}}\right]^{1/\rho_{r,t}} \quad \text{Eq. 5-23}$$

6 Scenario analysis

This chapter presents how the TIAM-MACRO model is applied to analyze long-term mitigation pathways of the global energy system. It starts by outlining the main scenario assumptions and the characteristics of the employed scenarios. Eight scenarios are defined to address the required energy system transformations the associated macroeconomic implications in order to meet a well-below 2°C consistent target. One of the scenarios applies the VES approach to provide more insights into the mitigation role of energy-service demand reduction. Finally, for different energy sectors, the relative roles of supply-side and demand-side measures in achieving the climate mitigation target are identified.

6.1 Scenario assumptions

This section elaborates the main scenario assumptions when applying the TIAM-MACRO model. According to Loulou et al. (2016a), within a TIMES model, a scenario is described by a set of coherent input assumptions which can be divided into four main components (Table 6-1).

Table 6-1: Four components of a scenario in the TIAM model

Scenario component	Description
Demand	The projection of socio-economic drivers of energy-service demands
Techno-economic	The techno-economic specifications of technologies and processes
Potential	The potentials for primary energy and material resources
Policy	The description of the implemented energy-related policies

6.1.1 Key socio-economic drivers of energy-service demands

To project energy-service demands in TIAM, it is essential to specify the regional socio-economic drivers. The basic demographic and economic assumptions are mainly adopted from a 2015 study of the United nations (UN, 2015) and a 2016 study of the International energy Agency (IEA, 2016b). Table 6-2 presents the key socio-economic assumptions (i.e., GDP and population) for the world and some example regions. Figure A-3, Figure A-4 and Figure A-5 in the Appendix provide a detailed presentation of the drivers.

The projections of the drivers are performed exogenously and kept identical across all scenarios in order to provide a similar starting point for all scenarios.

Table 6-2: Key socio-economic assumptions for the world and some example regions (annual growth rates)

Category	2015-2020	2020-2030	2030-2050	2050-2100
Global				
GDP[a] (%)	3.7	3.8	2.8	2.3
Population (%)	1.1	0.9	0.7	0.3
China				
GDP[a] (%)	6.5	5.3	2.7	1.8
Population (%)	0.5	0.1	-0.2	-0.6
India				
GDP[a] (%)	7.5	6.6	4.5	2.9
Population (%)	1.2	0.1	0.6	-0.1
USA				
GDP[a] (%)	2.5	2	1.8	1.5
Population (%)	0.7	0.7	0.5	0.3
Western Europe				
GDP[a] (%)	2.2	2	1.6	1.4
Population (%)	0.2	0.2	0.0	-0.1

a) GDP Growth rates are based on GDP in United States dollar in purchase power parity (PPP) constant 2014 terms

As discussed in chapter 3, one of the key socio-economic assumptions of the TIAM model is concerning the discount rate. A review of other global optimization models, such as PRIMES (E3Mlab, 2010) and MERGE (Manne and Richels, 2005), shows that they mostly assume a real discount rate of 5%. However, García-Gusano et al. (2016) who exclusively studied the role of discount rate in optimization energy system models, found 5% a "conservative assumption". In essence, the discount rate can vary from region to region according to their different investment risks. In less-developed regions it makes sense to have a higher discount rate (around 5%), while in other regions, due to less risks and uncertainties the discount rate should be lower (around 3%). In this dissertation the social discount rate for all regions in the TIAM model is set to 4%.

6.1.2 Techno-economic assumptions of the mitigation technologies

Since the electricity sector plays a substantial role in the climate change mitigation context, this section briefly presents the projections of the techno-economic characteristics of the included generation technologies. Even though the realization of further learning effects can be given as a function of the rate of expansion of technologies on a global level, in the analysis at hand, all learning rates are given exogenously. The investment cost assumptions are mainly based on a 2014 report of IEA titled "World Energy Investment Outlook" (IEA, 2014a) and a 2015 report of IEA titled "Projected Costs of Generating Electricity" (IEA, 2015b). As presented in Figure 6-1 and Figure 6-2, while no notable cost digressions are expected in the case of non-renewable power plants, further substantial learning effects are laid down for most of the renewables, especially solar PV, solar CSP, wind energy and ocean energy.

Note that in this study the United States Dollar (USD) in 2005 is used as the unit of currency.

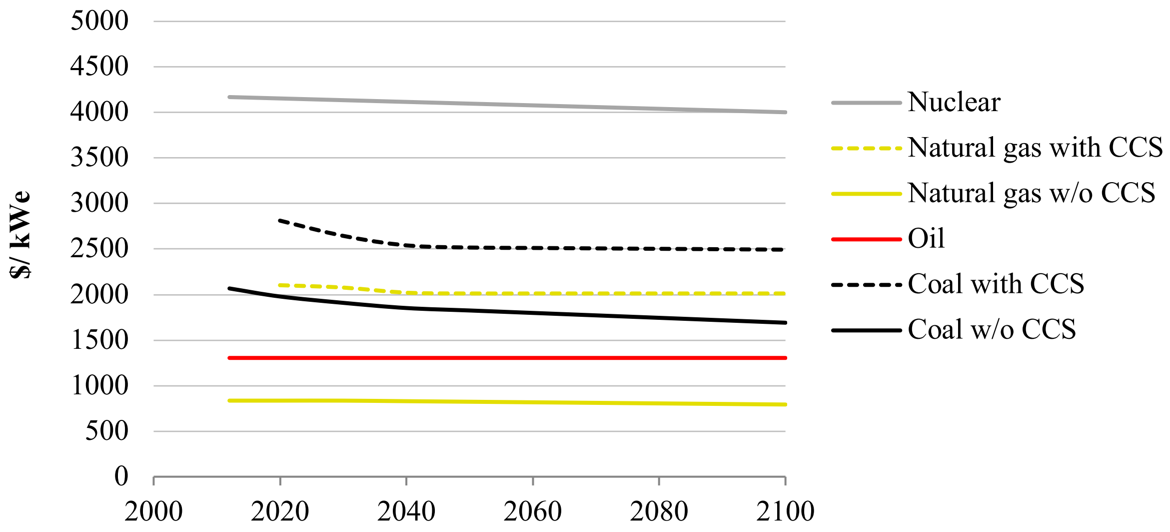


Figure 6-1: Average investment cost (over regions and technologies) for non-renewable electricity generation technologies in the TIAM model

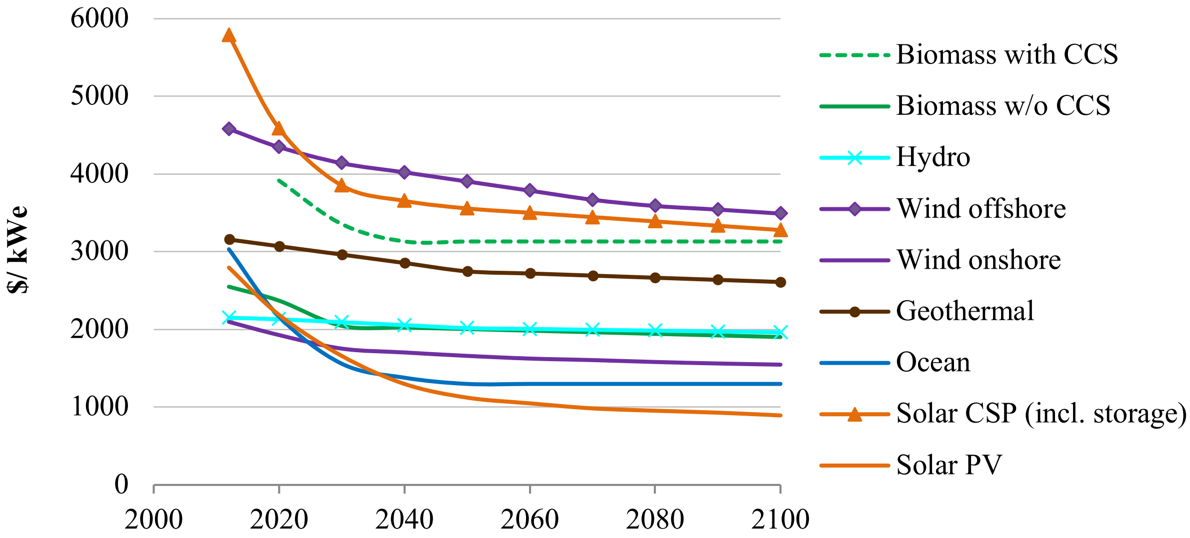


Figure 6-2: Average investment cost (over regions and technologies) for renewable electricity generation technologies in the TIAM model

In addition, the model considers, in a simple way, the costs for reinforcing and expanding the electricity grid that arise as a result of the growing shares of spatially distributed fluctuating renewable generation. In this regard, specific additional transmission and distribution grid costs per unit of installed capacity of solar PV and wind onshore/offshore are included. The values for the additional grid cost components are given in Table A-7 in the Appendix.

On the other hand, two key technical specifications of the power plant technologies are efficiency and capacity factor. Figure A-6 and Figure A-7 in the Appendix summarized the efficiency and capacity factor input assumptions for the power technologies, which are mainly provided based on IEA (2016d), IRENA (2015) and REN21 (2016) reports.

6.1.3 Fossil fuel prices

Fossil fuel prices are determined based on the new policy scenario of World Energy Outlook study in 2017 (WEO, 2017). Since the prices keep supply and demand for each fuel in equilibrium, the given trajectories (Table 6-3) are smoothly increasing and do not attempt to consider the fluctuations that characterize the fuel market in reality. The model differentiates between regional fuel prices by considering intra-regional trade costs.

While the tax implied by a decarbonization scenario influences the shadow price of a fossil fuel, other policy measures applied to fuel services (such as subsidies) are not considered in this dissertation.

Table 6-3: Average international fossil fuel import prices

		2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil	$/barrel	64.4	79.7	93.7	107.8	119.5	125.1	129.3	132.1	134.7
Natural gas	$/Mbtu	5.1	5.2	5.5	5.6	5.9	6.1	6.3	6.5	6.8
Coal	$/tonne	39.9	45.7	52.9	60.9	67.9	74.2	78.5	81.5	83.4

6.1.4 Potentials for low- and zero-carbon technologies

Mitigation technologies represent a cornerstone to steer our energy system in the direction of a decarbonized and sustainable one. However, the deployment of mitigation technologies is limited to certain technical and political bounds. For instance, while the availability of suitable land areas is a technical constraint for wind power plants, large-scale bioenergy production is subject to sustainability concerns. Therefore, for a comprehensive investigation of the role of these technologies in tackling climate change, it is of crucial importance to consider their maximum technical potentials and prospects for each world region. It is important to note that for most resources, technical potential is a changing factor. In fact, with increased research and development, the technical potential might be increased.

The assessment of the technical potential for renewables is based on a review of the existing literature and on the refinement of available data. Table 6-4 compares the estimates on renewables global technical potential.

Table 6-4: A review of estimates of renewables global technical potential[15] (EJ/Year)

Source	Solar	Wind	Ocean	Hydro	Biomass	Geothermal	
						Power	Heat
Sims et al. (2007)	1650	600	7	62	250	NA	5000[a]
Resch et al. (2008)	1600	600	NA	50	250	NA	5000[a]
Hoogwijk and Graus (2008)	2700	400	329	50	343	45	5000
Klimenko et al. (2009)	2592	191	22	54	NA	22	NA
Cho (2010)	1577	631	NA	57	284	NA	120
Tomabechi (2010)	1600	700	11	59	200	NA	310000[a]
WEC (2010)	NA	NA	7.6b	57	NA	1.1-4.4	140
WBGU (2011)	280000 (10000[b])	1700 (1000[b])	NA	160 (12[b])	800 (100 [b])	NA	720 (22[b])

a) Covers both electricity and direct heat
b) Sustainable potential

To determine the potentials for renewables in the TIAM model, for each source, the distribution of the estimates is taken into account. Accordingly, a value which is in-line with most of the estimates is selected. This being so, outliners or the estimates which are significantly different with others are left out of consideration. For solar, for instance, the estimate given by WBGU (2011) is not taken into account. Table 6-5 presents the assumed global technical potential for renewables in the TIAM model.

Table 6-5: The global technical potential for renewables in the TIAM model

	Solar	Wind	Ocean	Hydro	Biomass	Geothermal	
						Power	Heat
Potential (EJ/Year)	1600	600	22	57	280	22	5000

However, it is unrealistic to assume that the given technical potentials can be realized in the short-term. Therefore, for a more accurate assessment of mitigation pathways, it is essential to consider realizable potentials which refer to the fraction of the overall technical potentials that can be actually realized in each time period.

To determine the realizable potential for renewables in each period, overall constraints such as planning requirements and industrial growth must be taken into consideration (IEA, 2015c). Several studies have discussed the global and regional realizable potential for renewables. The current study mainly benefits from IEA technology roadmap reports for hydropower

[15] In terms of primary energy supply

(IEA, 2012), geothermal heat and power (IEA, 2011), solar thermal electricity (IEA, 2014c), solar photovoltaic (IEA, 2014c) and the 2014th report of Global Wind Energy Council (GWEC, 2014). Figure 6-3 illustrates the realizable global potential for renewables in the TIAM model. As depicted, it is assumed that the technical potentials can be realized at the end of the century.

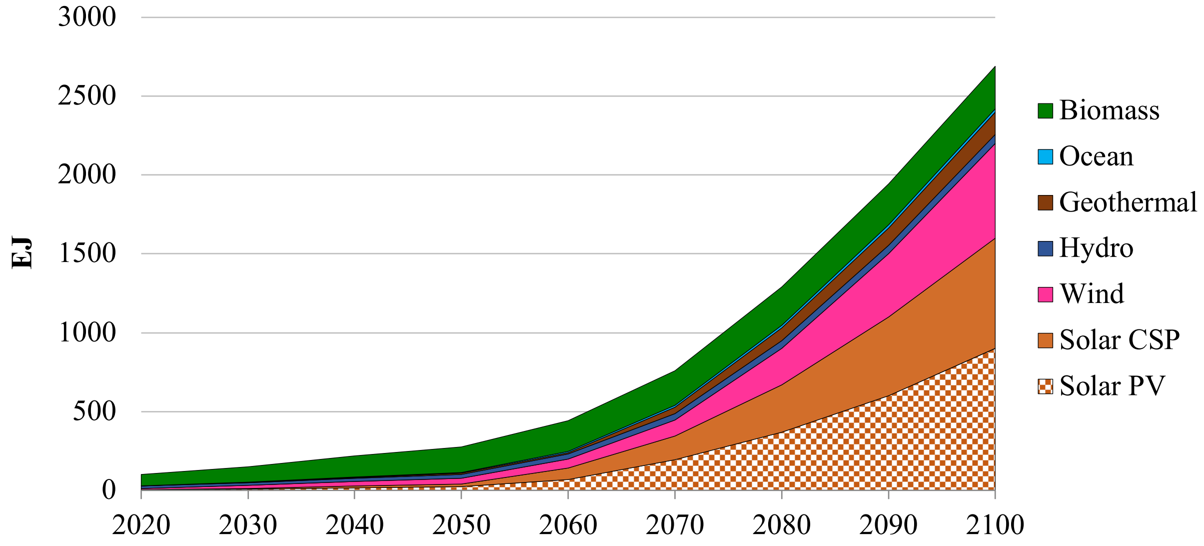


Figure 6-3: The realizable global potential for renewables over the century in the TIAM model (geothermal represents only geothermal electricity)

One of the mitigation measures is deployment of CCS technologies. However, it is essential to assess if the availability of geologic CO_2 storage capacity influence the future role of CCS technologies. This has been the subject of debate since the 1990s (Dooley, 2013a). Table 6-6 presents a review of recently published estimates of the global deep geologic CO_2 storage capacity.

It can be seen the potential for global CO_2 storages is surrounded by notable uncertainty. This is especially the case for aquifers. The values used in this study is based on the “best estimate” of Hendriks et al. (2004) that has been used by various studies (e.g., Selosse et al., 2013b and Rösler et al. 2014). While the given values in this study for oil and gas fields and coal beds are in good agreement with the other sources, for aquifers, it provided a more conservative estimation. Considering the huge uncertainty that surrounds the potential of this type of CO_2 storage, this is a more reasonable assumption for the current study.

The given CO_2 storage potential in the world and in many key regions theoretically appear to be more than enough to meet current and future demand from nearby CO_2 emissions sources for at least the current century. However, risk assessment is a vital requirement for the selection of appropriate sites for long-term storage of CO_2 emissions. According to Global CCS Institute (2012), while geologic uncertainties or risks are highly site-specific, one of the main perceived risks of carbon storages regards their potential impacts on environment and health and consequently, the social acceptability of CCS technologies. In this regard, due to the public resistance against onshore CO_2 storages (see e.g., Mendelevitch et al., 2010; Selosse et al., 2013), this study assumes a conservative approach by excluding them.

Table 6-6: A literature review on estimates of potential for various underground CO_2 storages (Gt)

Source:		IPCC (2005)	Manancourt and Gale (2005)	Dooley et al. (2006)	Dooley (2013)		Hendriks et al. (2004)		
					Effective	*Practical*	*Low estimate*	*Best estimate*	*High estimate*
CO_2 storage type	Coal beds	3-200	150-250	176	13500*	3900*	0	267	1480
	Saline aquifers	1000 - 10000	200 -200000	9530			30	240	1080
	Oil & gas fields	675 - 1200	500 - 1000*	810*			446	1153	3320
Total		1678 - 11400	850 - 201250	10336	13500	3900	476	1660	5880

* Remaining oil and gas fields are not included

Figure 6-4 illustrates the assumed global cumulative potential for the offshore CO_2 storage sites. The regional distribution of the total offshore CO_2 storage potential is depicted in Figure A-8 in the Appendix.

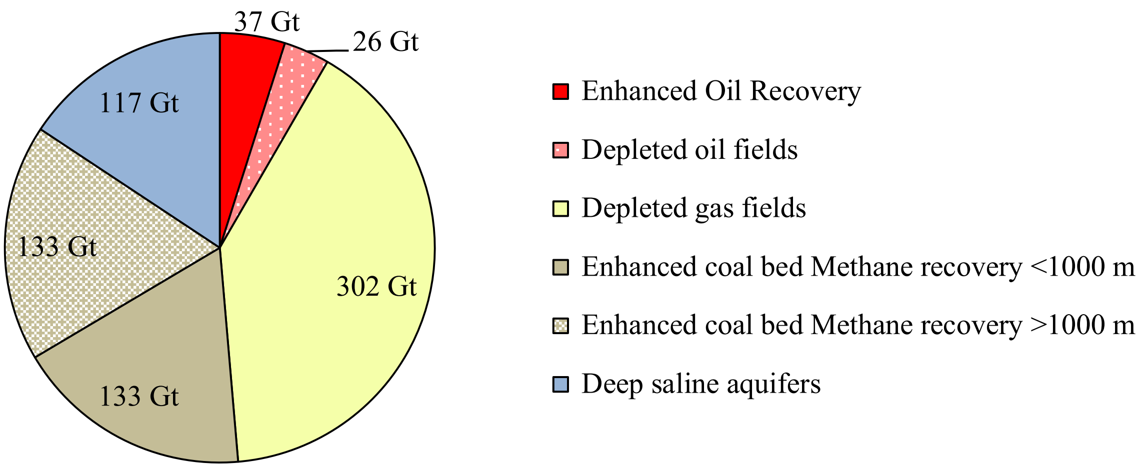


Figure 6-4: The global cumulative potential for offshore CO_2 storage sites in the TIAM model

The deployment of nuclear, as a mitigation measure, is also subject to some limitations (e.g. resource availability). The International Atomic Energy Agency (IAEA) in its 2010 and 2013 reports (IAEA, 2010; IAEA, 2013) presented different projection pathways for global and regional nuclear capacity growth. The maximum capacity of nuclear power until 2050 is assumed to be equal to the 'High growth' pathway of IAEA (2013). However, considering the socio-political barriers against nuclear power, which arise uncertainty in its deployment, the maximum capacity in the long-term is set close to the conservative 'Low growth' case of IAEA (2010) (Figure 6-5).

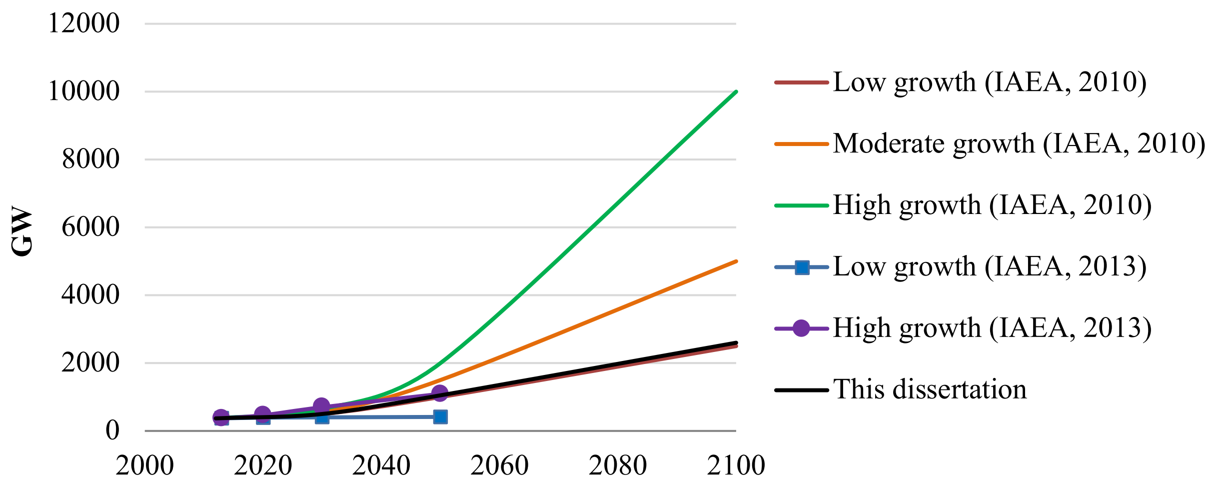


Figure 6-5: World nuclear power maximum installed capacity projection pathways in the IAEA reports and in the TIAM model

Besides the input assumptions of the TIAM model, it is necessary to establish a set of consistent assumptions for the MACRO model as well. One of the most critical assumptions is concerning the size of the elasticity of substitution. While, the assumed value for the elasticity of substitution in the standard MACRO model is discussed in chapter 5, this chapter presents the assigned values for each region and time period in the VES case (that is applied in one of the scenarios).

The VES in this dissertation reflects that lower elasticity of substitution tightens the linkage between income growth and increase in energy-service demand. To specify the regional elasticity of substitutions in the first planning period (i.e., 2015-2020), adapted from World Bank (2017), the model regions are divided into high-income, middle-income and low-income regions with elasticities of 0.25, 0.2 and 0.15, respectively (Table 6-7).

As discussed above, to determine the elasticity values for the next years (i.e., 2021 to 2100) it is assumed that the elasticity of substitution of each region is a linear function of GDP per capita growth of the region. However, in order to avoid overestimations and stay in the range (discussed in Chapter 5), the maximum elasticity parameter (for India in 2100) is set to 0.5. Accordingly, the elasticities for all the other regions/time periods are scaled. While in the CES case the elasticity of substitution is 0.25 for all regions over the entire time horizon, Figure 6-6 depicts the given values for substitution elasticities in the VES case.

Table 6-7: Classification of the model regions and the associated elasticity of substitution in 2020

Economic level	Regions	Elasticity of substitution
High income	USA, Western Europe, Canada, Japan, South Korea, Australia	0.25
Middle income	Eastern Europe, Middle-East, China, Mexico, Central and south America, Former soviet union, Other Asia	0.2
Low income	India, Africa	0.15

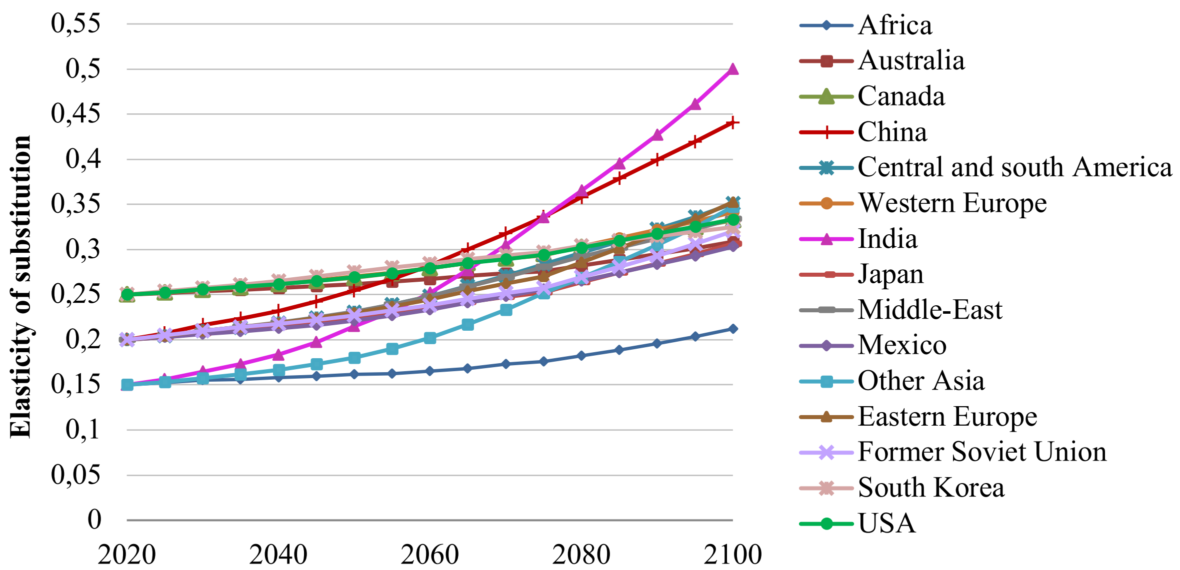


Figure 6-6: Region- and time-dependent elasticity of substitutions in the VES case

The other input parameters of the TIAM-MACRO linkage are listed in Table 6-8. All the presented input parameters are adapted from the original MACRO model (Remme and Blesl, 2006).

Table 6-8: The other input parameters of the TIAM-MACRO linkage

Parameter	Description	Value
DEPR	Depreciation rate	5%
KPVS	Share of capital in the sum of all production factors in first period	0.25
KGDP	Capital-to-GDP ratio in the first period	2.5

6.1.5 Energy sector CO_2 emissions budget

The Paris agreement sets a globally agreed target of limiting future temperature increases to well below 2°C above pre-industrial levels. However, as discussed in the Chapter 1, the agreement did not clearly define what would constitute a well-below 2°C outcome. While discussions on this continue, the objective has been interpreted to fall within the range of a high chance of keeping global average temperatures below 2°C and a reasonable chance of achieving a 1.5°C target. This dissertation translates this target to a 66% chance of meeting a 2°C target, which is adapted from IEA (2017).

For the purposes of the decarbonization scenarios, the total CO_2 budget consistent with the well-below 2°C, must contain both energy sector and non-energy sector CO_2 emissions. The energy sector carbon budget (including emissions from industrial processes as well as fuel combustion) is calculated from an estimate of the total CO_2 emissions budget for the given temperature limit (see IPCC, 2014 and IEA, 2017). Non-energy sector CO_2 emissions that mainly arise through land-use, land-use change and forestry (LULUCF) are given (exogenously) based on IEA (2017). Accordingly, in the decarbonization scenarios, it is assumed that total LULUCF emissions are around zero in 2045 and turn negative afterward. The net LULUCF CO_2 emissions over the period 2015-2100 are estimated at - 30 $GtCO_2$. The assumed carbon budget for the energy sector over the period 2015-2100 is presented in Table 6-9. It is noteworthy that this dissertation does not assume any direct constraint on the non-CO_2 GHG emissions.

Table 6-9: CO_2 budget assumptions in this study

Net anthropogenic warming with a probability of more than 66%	Total CO_2 budget (2015-2100)	Non-energy CO_2 emissions (2015-2100)	Energy sector CO_2 budget (2015-2100)
<2°C	720 $GtCO_2$	-30 $GtCO_2$	750 $GtCO_2$

6.2 Scenario characteristics

With the aim to explore the relative roles of supply-side and demand-side measures in tackling global climate change, a set of scenarios have been developed (Table 6-10). To develop these scenarios, five critical questions have been considered:

- How will the global energy system look without any CO_2 reduction policies under the current political framework conditions (i.e., Business as Usual)?
- What are the energy system transformations and the associated macroeconomic implications required in order to meet the well-below 2°C target?
- How are the global mitigation pathways influenced by the potentials of the mitigation technologies?
- What are the impacts of energy-service demand reductions on global decarbonization pathways?
- How does the mitigation role of price-induced energy-service demands in the VES case change in comparison to the CES approach?

In this context, the Base scenario (no CO_2 reduction constraints) is employed as a benchmark for the decarbonization scenarios. As earlier discussed, for a more comprehensive understanding of the contribution of technological options, the described technical potentials and availability limitations of the mitigation technologies are seen in a dynamic context, which may increase over time. In four decarbonization scenarios, it is assumed that the potentials for nuclear, CO_2 storages, biomass and non-biomass renewables are 25% higher than the potentials given in the standard model.

On the other hand, due to uncertainties in the contribution of price-induced energy service demands reductions, decarbonization scenarios vary depending on their assumption concerning this mitigation measure. One of the scenarios (B2D-DEM) ignores the interconnection between energy-service demands and their prices in order to rely on technological mitigation measures. Moreover, to provide more detailed insights into the role of price-induced energy-service demand reductions, one of the scenarios (B2D-VES) includes the presented VES approach. In this scenario, the elasticity of substitution varies as in Figure 6-6.

Table 6-10: Observed scenarios

Scenario	CO_2 reduction policy	Potential for non-bio renewables	Potential for carbon storages	Potential for biomass	Potential for nuclear	Elasticity
Base	×	Standard	Standard	Standard	Standard	-
B2D	✓	Standard	Standard	Standard	Standard	0.25
B2D+REN	✓	25% higher	Standard	Standard	Standard	0.25
B2D+CCS	✓	Standard	25% higher	Standard	Standard	0.25
B2D+BIO	✓	Standard	Standard	25% higher	Standard	0.25
B2D+NUC	✓	Standard	Standard	Standard	25% higher	0.25
B2D-DEM	✓	Standard	Standard	Standard	Standard	-
B2D-VES	✓	Standard	Standard	Standard	Standard	*

* Elasticity of substitution varies as in Figure 6-6

It is noteworthy that a number of studies dealing with ambitious global mitigation measures, have allowed for temporary overshooting of the carbon budget that must be later counterbalanced with deployment of negative emissions technologies in later periods (e.g. Rogelj et al. 2015, Luderer et al. 2013). Nevertheless, several scientists believe that negative impacts of atmospheric CO_2 emissions are not always reversible (Tokarska and Zickfeld, 2015). They argue that a decline in atmospheric CO_2 does not result in a simultaneous decrease in global temperature and the heat stored in the oceans continues to be released for centuries onward. Furthermore, even by using significant negative emissions, sea level rise is not reversible for at least several centuries. Therefore, in this dissertation, any overshooting of the carbon budget over the century is prohibited.

6.3 Scenario results

In order to provide a systematic analysis of the needed mitigation measures and the associated costs to meet the well-below 2°C target, several aspects of the global energy system are discussed here. While some results present the required energy system transformations for moving from the Base scenario to the B2D in a detailed manner, some others focus on specific mitigation measure and compare the relevant scenarios. Furthermore, to provide a more comprehensive assessment, macroeconomic implications of the decarbonization scenarios are discussed.

The statistical data and information (e.g., data for primary energy consumption, gross electricity generation and CO_2 emissions) up to 2015 are based on IEA statistics (IEA, 2016d).

6.3.1 Primary energy consumption

In 2014, global total primary energy consumption was 569 EJ with oil accounting for about 32%, coal 29%, natural gas 21%, biomass and waste 10%, nuclear 5% and other (non-biomass) renewables 3%.

For the Base and B2D scenarios, Figure 6-7 illustrates the global primary energy consumption mix in 2014 and 2100 and the corresponding fossil fuel and non-fossil fuel changes over the period. It can be seen that the overall primary energy in the Base increases by 132% from 2014 levels to reach 1318 EJ in 2100 at an average annual rate of 1%. While fossil fuels continue to dominate primary energy consumption, their total share declines from 82% in 2014 to 66% in 2100. This represents an absolute increase in fossil fuel consumption of around 405 EJ, compared with 2014 levels. The remaining primary energy mix of the Base in 2100 consists of biomass and waste (18%), other renewables (8%) and nuclear (8%).

Similar to the Base, in the B2D, total primary energy consumption grows over time, but at a lower rate. It is seen that the overall global primary energy consumption in this scenario increases by 91% from 2014 to 2100. In contrast to the Base, reliance on fossil fuels in the B2D falls dramatically to just 14% of the mix in 2100, with an absolute decline in consumption of around 309 EJ, or 67% lower than the 2014 consumption level. Primary coal consumption declines by 90%, oil by 51% and natural gas by 58%, compared with 2014 levels. It will be later discussed that most of the remaining fossil fuels are used either in combination with CCS technologies or as feedstocks and other non-energy purposes.

In the B2D scenario, renewables overtake fossil fuels to dominate the primary energy mix by a share of 68% (743 EJ) in 2100. This represents an addition of 528 EJ from 2014 to 2100, an increase equal to 93% of today’s total primary energy consumption. The share of biomass and waste reaches 27% (294 EJ) of the primary energy mix in 2100, representing around five times higher than current levels of biomass and waste consumption. The remainder of the primary energy mix in 2100 is nuclear with a share of 18% (198 EJ).

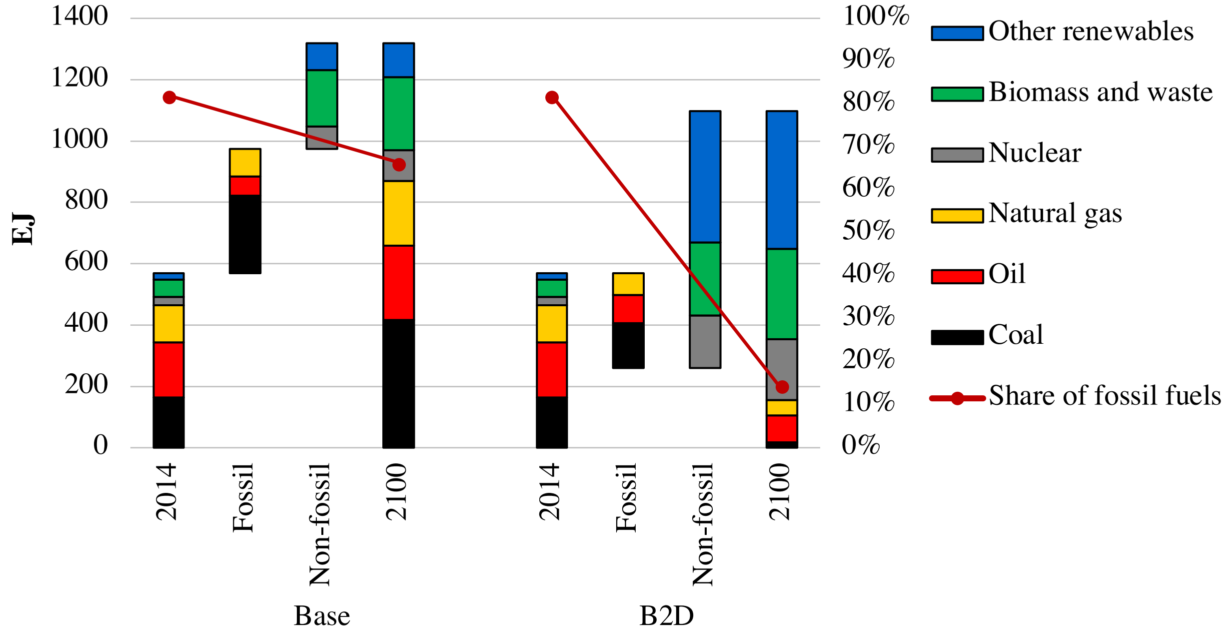


Figure 6-7: Global primary energy consumption by resource in the Base and the B2D

6.3.2 Final energy consumption

In 2014, total final energy consumption was around 402 EJ, with the mix of oil products (39%), electricity (18%), coal (15%), natural gas (14%), biomass and waste (10%) and heat[16] (3%). The share of other renewables was less than 1%. OECD countries and Non-OECD accounted for 40% and 60% of the final energy consumption, respectively.

Figure 6-8 shows that final energy consumption in the Base reaches 1000 EJ in 2100, an increase of around 150% from 2014 levels. The average annual growth in the period 2014 to 2100 is 1.1%. Since there is no constraint on CO_2 emissions in the Base scenario, coal remains the dominant fuel in this scenario with a 24% share in 2100, followed by oil with 23%. While natural gas's contribution increases slightly from 14% in 2014 to 17% in 2100, the shares of electricity and biomass remain stable at around 18% and 10%, respectively. The remainder of the final energy consumption mix of the Base in 2100 is other renewables (5%), heat (1%) and others[17] (2%). CO_2 intensity of final energy use in this scenario remains almost the same as today's levels (48 gCO_2/MJ).

While non-OECD countries increase their final energy consumption by more than 200% from 2014 to 2100, in OECD countries the increase is limited to 55%. Although on average the final energy consumption per capita remains higher for OECD countries, it grows much more rapidly in non-OECD countries. This reflects markedly different paths in industrialized

[16] "Heat" refers to commercial heat provided by heat networks
[17] It includes hydrogen and non-renewable wastes

countries from those in developing countries. The latter countries are expected to have considerably higher economic growth over the coming decades, leading to a relatively high level of final energy demand in these countries.

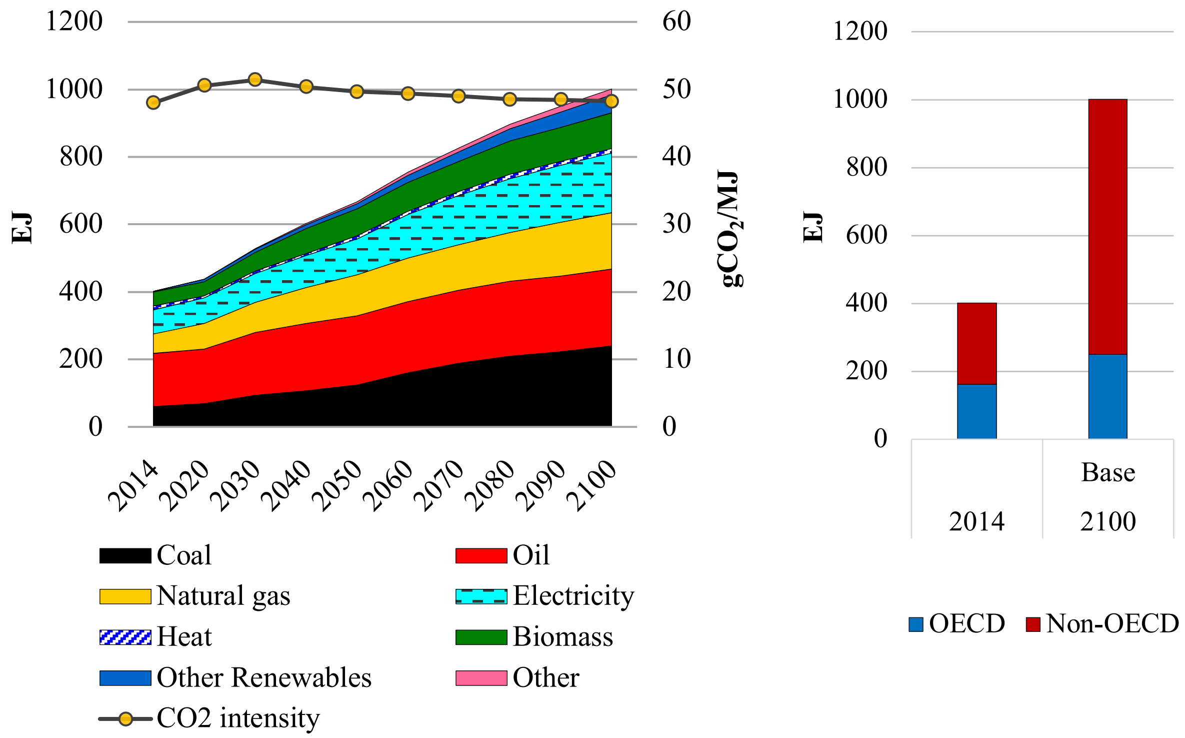


Figure 6-8: Global final energy consumption by energy carrier and region in the Base

As depicted in Figure 6-9, in the B2D, final energy consumption still increases, but at a much slower pace than in the Base, reaching 778 EJ by 2100. Almost 75% of the global final energy consumption in 2100 is derived by non-OECD countries. The final energy consumptions of non-OECD and OECD in the B2D are 23% and 22% lower than those in the Base, respectively.

In this scenario, the decomposition of final energy use changes radically compared with the Base. While fossil fuels remain the largest source of the final energy consumption in the Base, their share declines from 67% in 2014 to only 14% in 2100 in the B2D. Electricity surpasses oil as the current most important energy carrier in the B2D with a share of 48% in 2100. Besides electrification, direct use of renewables (including biomass) plays an important role in decarbonizing the final energy consumption, providing more than 27% of the mix in 2100. Commercial heat consumption shows a significant increase from 11 EJ (1%) in 2014 to 66 EJ (8%). The remainder of the final energy mix in 2100 in the B2D is other fuels with a share of 3%. CO_2 intensity in this scenario experiences a rapid and strong reduction from 48 gCO_2/MJ in 2014 to 4 gCO_2/MJ in 2100. The remaining emissions at the end of the century are mainly derived from the industry and transport sectors.

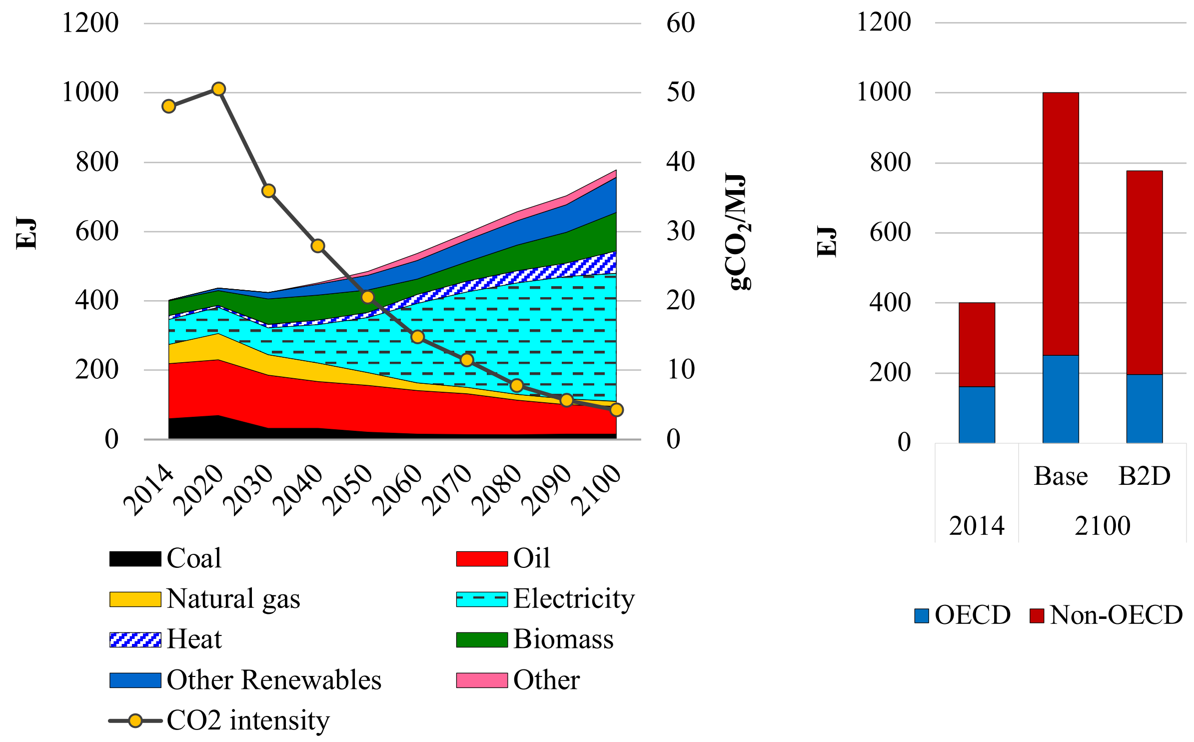


Figure 6-9: Global final energy consumption by energy carrier and region in the B2D

6.3.3 CO_2 emissions

Global CO_2 emissions from energy and industry-related sources were around 34.2 $GtCO_2$ in 2014. The emissions were mainly from the following sectors: electricity (40%), industry (24%), transport (22%), buildings[18]/agriculture (10%) and other transformation[19] (4%). However, if CO_2 emissions from the electricity and other transformation sectors are allocated to the end-use sectors, the shares of industry and buildings/agriculture would rise noticeably to around 41% and 32%, respectively. It is noteworthy that almost half of the overall CO_2 emissions are produced in China and the USA.

In the Base, CO_2 emissions more than double (compared with 2014 levels) to reach around 70 $GtCO_2$ in 2100. As depicted in Figure 6-10, the share of different sectors in total emissions changes significantly over the century. Industry becomes the largest source of CO_2 emissions, constituting more than 46% of the overall CO_2 emissions in 2100. Due to the penetration of renewables and nuclear, CO_2 emissions from electricity generation rise only slightly over the century and its relative growth rate slows down, notably. In 2100, only 22% of CO_2 emissions are from the electricity sector. While the share of buildings and agriculture in the overall produced CO_2 emissions remains almost constant over the century, transport reduces its contribution from 22% in 2014 to 15% in 2100, mainly due to greater use of biofuels and natural gas.

China remains the top CO_2 emitter in the world with an almost stable share of 30%. However, due to the expected high economic growth of India over the century, this country presents

[18] Includes the residential and commercial sectors
[19] Other fuel transformation processes including petroleum refineries

the most rapid increase in CO_2 emissions with an annual rate of 1.6%. it is expected that developing countries will present unforeseen decarbonization challenges in the future that have not yet seen. On the other hand, it can be concluded that achieving the B2D will require a substantial decoupling between CO_2 emissions and economic growth.

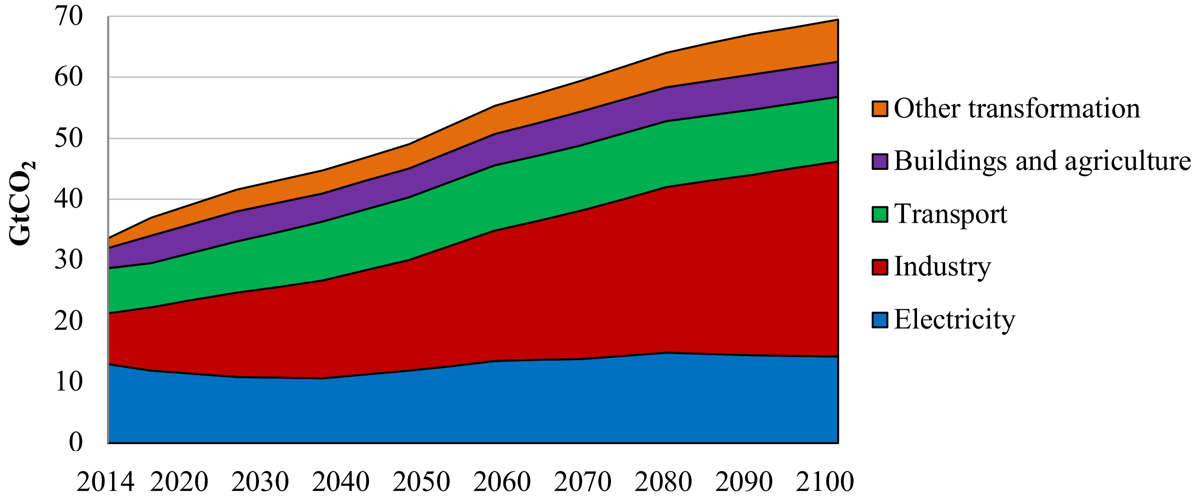


Figure 6-10: Global CO_2 emissions by sector in the Base

In the B2D, CO_2 emissions peak in 2020 and rapidly decline in order to reach carbon neutrality from around 2065 onwards (Figure 6-11). It is noteworthy that CO_2 emissions fall dramatically in the first decade of action (i.e. 2020-2030). This conveys a clear message that early action in all sectors and countries is critical to meeting the long-term well-below 2°C target. Hence, for an effective shift, considerably broad and comprehensive mitigation policies are necessary to be implemented as soon as possible. Policy makers must support measures that avoids the lock-in of carbon-intensive technologies. Examples include, eliminating fossil fuel subsidies, phasing out inefficient coal power plants, encouraging development and deployment of more efficient and less carbon-intensive technologies, as well as promoting investment in innovation across all energy sectors.

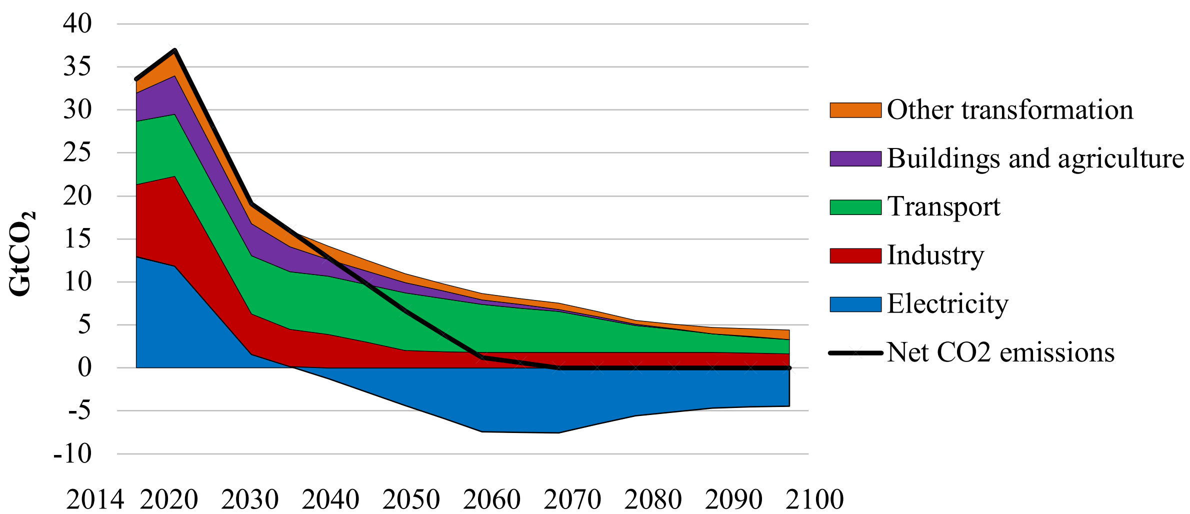


Figure 6-11: Global CO_2 emissions by sector in the B2D

The cumulative carbon budget in the B2D over the period of 2015 to 2100 is about 85% lower than in the Base, meaning an abatement of more than 4100 $GtCO_2$ emissions over the period. It can be seen in Figure 6-11 that all sectors of the energy system must significantly contribute to achieve the well-below 2°C target. However, due to the notably high flexibility of the power sector in deploying zero- and low-carbon technologies, the most rapid decarbonization happens in this sector. In fact, the power sector becomes carbon-neutral around 2040 and carbon-negative over the period 2040-2100. Negative emissions are vital in offsetting remaining emissions from other sectors where direct abatement is either too expensive or technically more difficult. As illustrated in Figure 6-11, the residual emissions of the energy system after 2070 are mainly from transport and industry.

Table 6-11 shows that more than 70% of the cumulative CO_2 emissions reduction in the B2D compared to the Base occurs in non-OECD economies. Therefore, developing low-carbon energy systems in emerging and emerging economies must be central to any cost-effective transition.

Table 6-11: Cumulative CO_2 emissions (2015-2100) by region in the Base and B2D

	World	**OECD**	**Non-OECD**
Cumulative CO_2 emissions ($GtCO_2$) in the Base	4863	1372	3491
Cumulative CO_2 emissions ($GtCO_2$) in the B2D	750	210	540
Cumulative CO_2 emissions reductions ($GtCO_2$) from the Base to B2D	4113	1161	2952

Although the B2D follows a rapid decarbonization pathway that does not result in any overshooting of the carbon budget (Figure 6-12), this is not to suggest that negative emissions technologies do not have an important role. Figure 6-13 illustrates that biomass with CCS (BECCS), accounting for a share of 16% of the cumulative emissions reduction, plays a substantial role to stay within the carbon budget and to reach carbon-neutrality by around 2065.

Despite the importance of BECCS, it is not the only required mitigation measure. In fact, to deliver the cumulative emissions reduction, the B2D needs contributions from a diversified mix of measures across all energy sectors. As depicted in Figure 6-13, renewables (excluding BECCS) is found to be the major contributor, accounting for about 42% of the cumulative emissions reduction over the period 2020-2100. In spite of the challenges and policies restricting nuclear power deployment, it represents a promising option for reducing emissions. In the B2D, nuclear ramps up its contribution toward the end of the century, cumulatively contributing 14%. In contrast, the increasing CO_2 price in the B2D reduces the attractiveness of fossil fuel CCS and fossil fuel switching options over time, which account for a 7% and 3% share, respectively. Due to the fact that energy efficiency measures that are cost-saving over the long run are already deployed in the Base, energy efficiency improvement does not represent a notable contribution to move from the Base to the B2D.

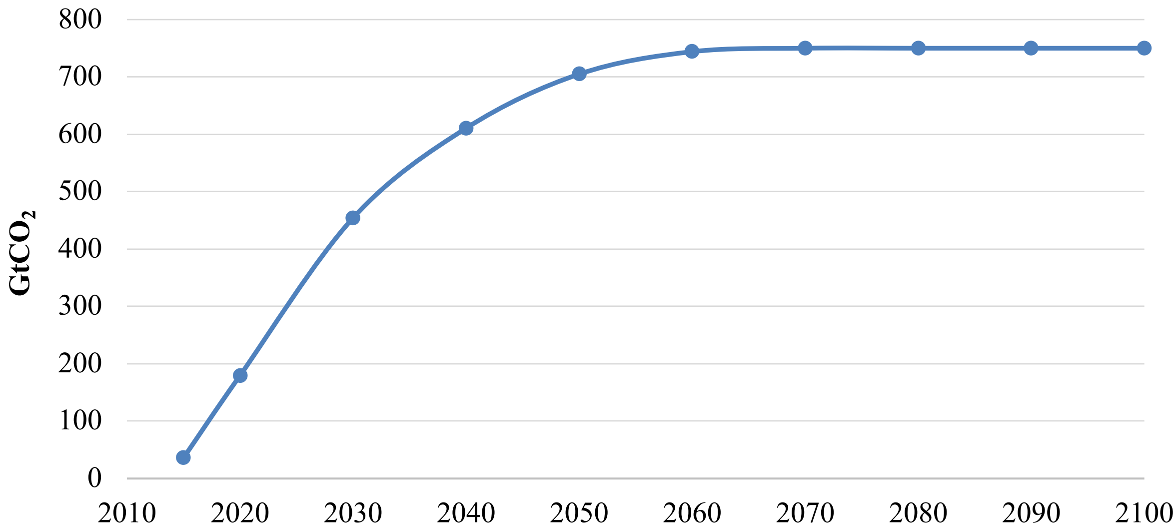


Figure 6-12: Global cumulative CO_2 emissions in the B2D

Despite the importance of BECCS, it is not the only required mitigation measure. In fact, to deliver the cumulative emissions reduction, the B2D needs contributions from a diversified mix of measures across all energy sectors. As depicted in Figure 6-13, renewables (excluding BECCS) is found to be the major contributor, accounting for about 42% of the cumulative emissions reduction over the period 2020-2100. In spite of the challenges and policies restricting nuclear power deployment, it represents a promising option for reducing emissions. In the B2D, nuclear ramps up its contribution toward the end of the century, cumulatively contributing 14%. In contrast, the increasing CO_2 price in the B2D reduces the attractiveness of fossil fuel CCS and fossil fuel switching options over time, which account for a 7% and 3% share, respectively. Due to the fact that energy efficiency measures that are cost-saving over the long run are already deployed in the Base, energy efficiency improvement does not represent a notable contribution to move from the Base to the B2D.

On the other hand, it can be seen that an optimal pathway toward well-below 2°C requires substantial reductions in energy-service demands. In the B2D, energy-service demand reduction is the second major measure, representing 22% of the cumulative emissions reduction. It can be concluded that energy-service demand reductions play a critical role in facilitating the transition.

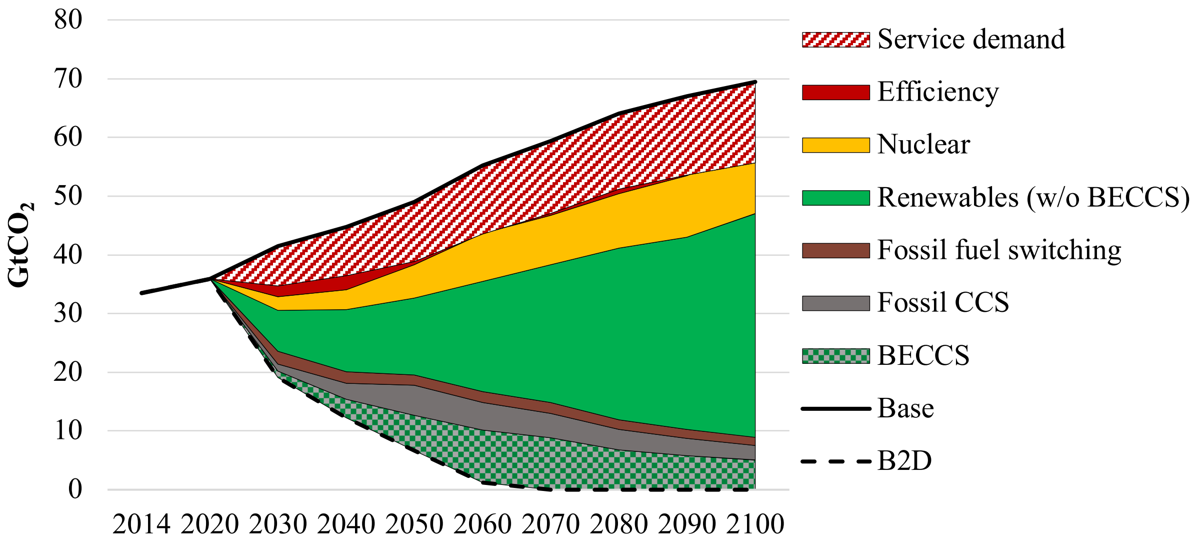


Figure 6-13: Global CO_2 emissions reductions from the Base to the B2D by mitigation measure

Based on our current understanding of energy technology development, the B2D scenario requires considerable investments in mitigation technologies to reach carbon neutrality by around 2065 and stay carbon neutral afterwards. As a result of such a rapid and deep decarbonization, CO_2 marginal abatement costs (equalized across regions) in the B2D increase over the century. Figure 6-14 illustrates that abatement costs follow an almost a linear pathway, reaching 1735 $/t$CO_2$ by the end of the century. According to Koljonen and Lehtilä (2012), this is way beyond reasonable levels.

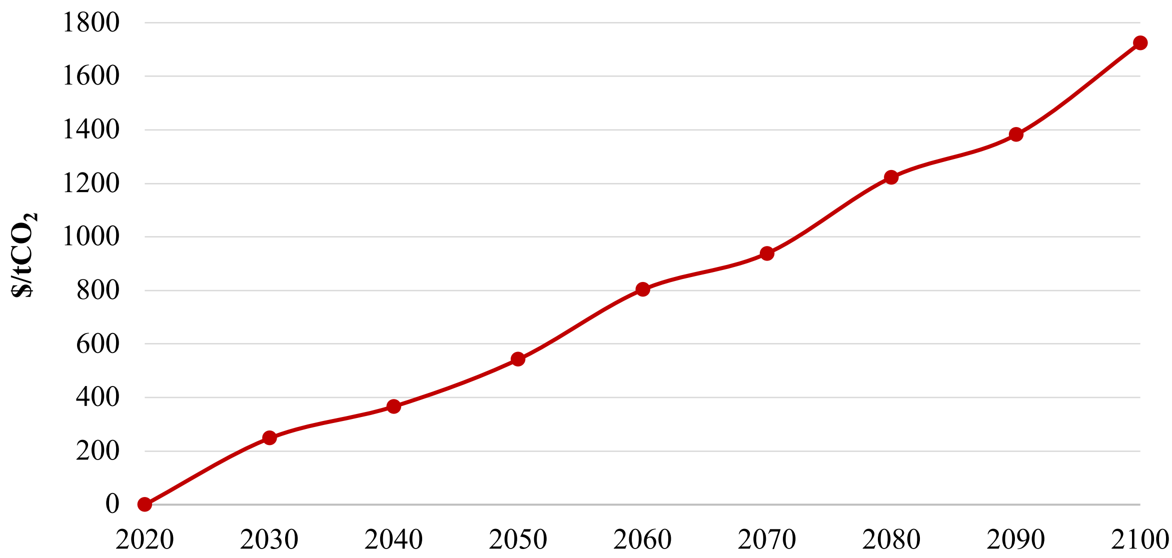


Figure 6-14: Annual CO_2 marginal abatement costs in the B2D

6.3.4 Decarbonization of the power sector

Ongoing global social and economic developments have increased electricity demand to 23.8 PWh in 2014. In particular, China and the USA together were responsible for more than 40% of the global electricity demand in 2014. According to IEA (2016b), global average per capita electricity consumption has more than doubled over last four decades. Despite the recent expansion of low-carbon technologies, the electricity generation mix in 2014 was dominated by fossil fuels with a share of 67%. Nuclear provided 11% of the electricity demand, while renewables accounted for 22% of the mix. More than 70% of the renewable-based electricity in this year was generated by hydropower.

In the Base scenario, global electricity demand rises to 55.7 PWh in 2100, an increase of 134% from 2014 levels (Figure 6-15). The average annual growth in the period 2014-2100 is almost 1%. The generation mix remains heavily dependent on coal providing around 36% (20.2 PWh) of electricity demand in 2100. However, expected cost reductions and rapid evolvement of low-carbon technologies lead to a notable penetration of these technologies. While nuclear generates 17% of the global electricity demand in 2100, renewables account for around 40%. Hydropower remains the largest source of renewable power, providing around 3.8 PWh (7%) of global final electricity demand in 2100. The deployment of low- and zero-carbon technologies accelerates recent trend of CO_2 intensity reduction in power generation. It can be seen that the CO_2 intensity of the global electricity sector falls from 519 gCO_2/kWh in 2014 to 255 gCO_2/kWh in 2100.

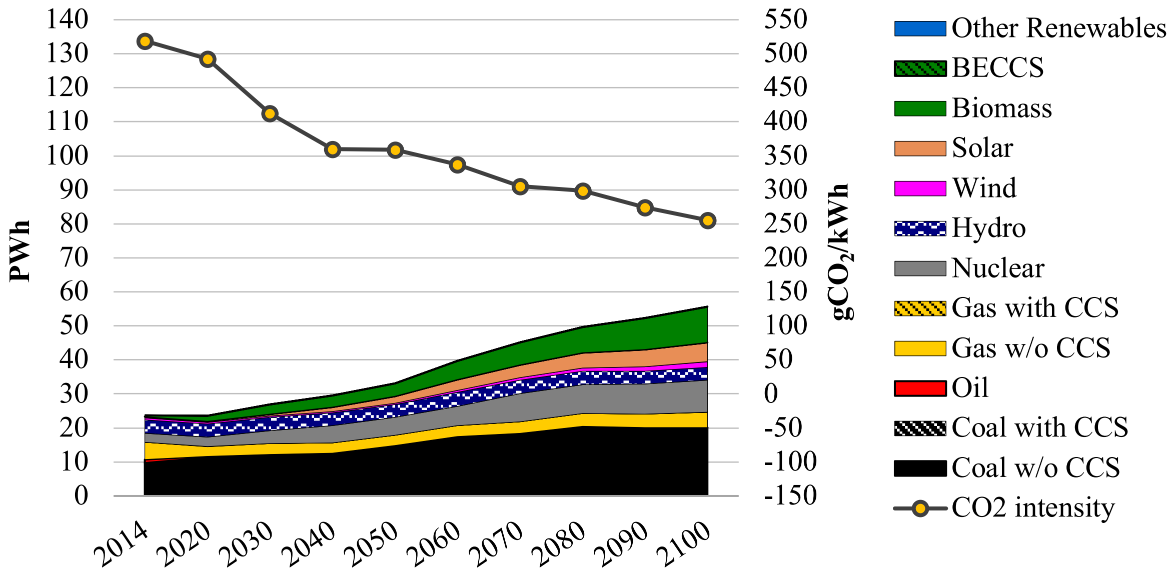


Figure 6-15: Global electricity generation mix and CO_2 intensity of electricity generation in the Base

Moving from the Base to the B2D entails a dramatic reduction in CO_2 emissions from the power sector. As presented in Figure 6-16, the power sector in the B2D reaches carbon-neutrality by around 2040. In fact, 12% share of BECCS turns the global electricity mix into a source of negative emissions over the period of 2040-2100. The CO_2 intensity of the sector in 2100 is -41 gCO_2/kWh. As stated earlier, negative emissions are needed to offset residual emissions from other sectors where direct mitigation is more challenging. In spite of the advances made in CCS technology in recent years, no large BECCS power plant operates today at a commercial scale.

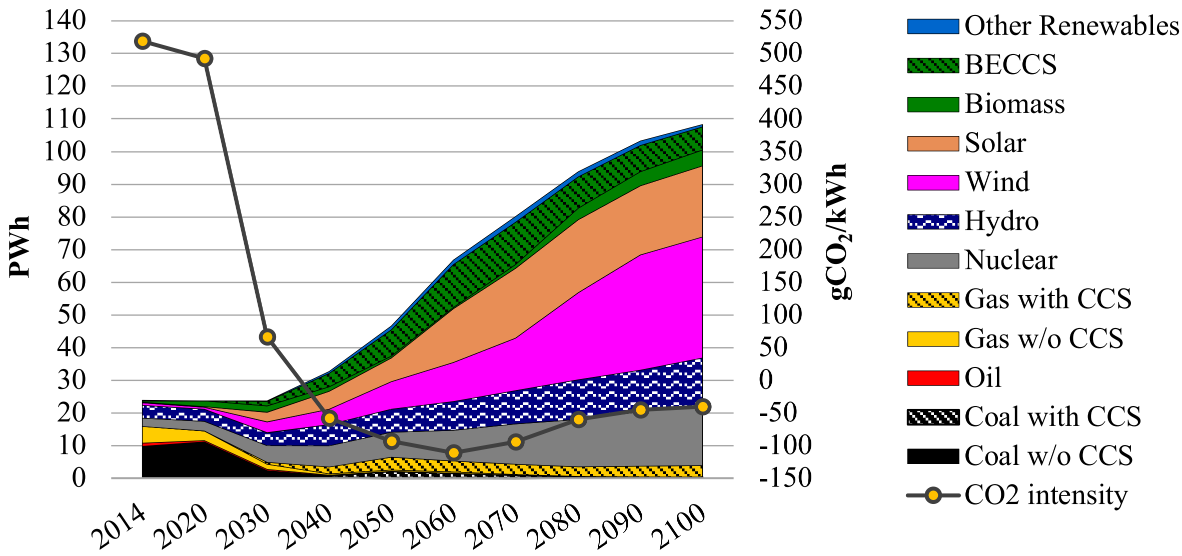


Figure 6-16: Global electricity generation mix and CO_2 intensity of electricity generation in the B2D

While conventional coal-fired power plants without CCS are phased out by 2040, due the relatively lower carbon intensity of gas-fired power plants, they continue longer until 2060. Considering the long technical lifetime of fossil fuel power plants, the early retirements of fossil fuel power plants affect current and near future investment decisions.

In the B2D, fossil fuel power plants with CCS are deployed from 2030 onward and peak at 2050. While initially CCS is applied to coal-fired power plants (mainly in China), as time passes, increasing CO_2 price makes gas-fired CCS more attractive than coal power plants with CCS. This is due to the relatively low remaining emissions of gas-fired CCS technologies.

The share of renewables (excluding BECCS) in the global electricity generation mix rises to 73% in 2100, accounting for 57 PWh more than in the Base. Variable renewable sources (e.g., solar PV and wind) which are non-dispatchable due to their fluctuating nature, account for more than 70% of the overall non-biomass renewables generation in 2100. Such a huge expansion in electricity generation from variable renewable sources necessitates the increased use of flexible power plants and other flexibility options. For instance, when solar PV is not generating enough electricity, a complementary source is needed to compensate.

Figure 6-17 shows changes to the global electricity generation mix in the B2D compared to the Base, which clearly reflects the important role of renewables in the transition.

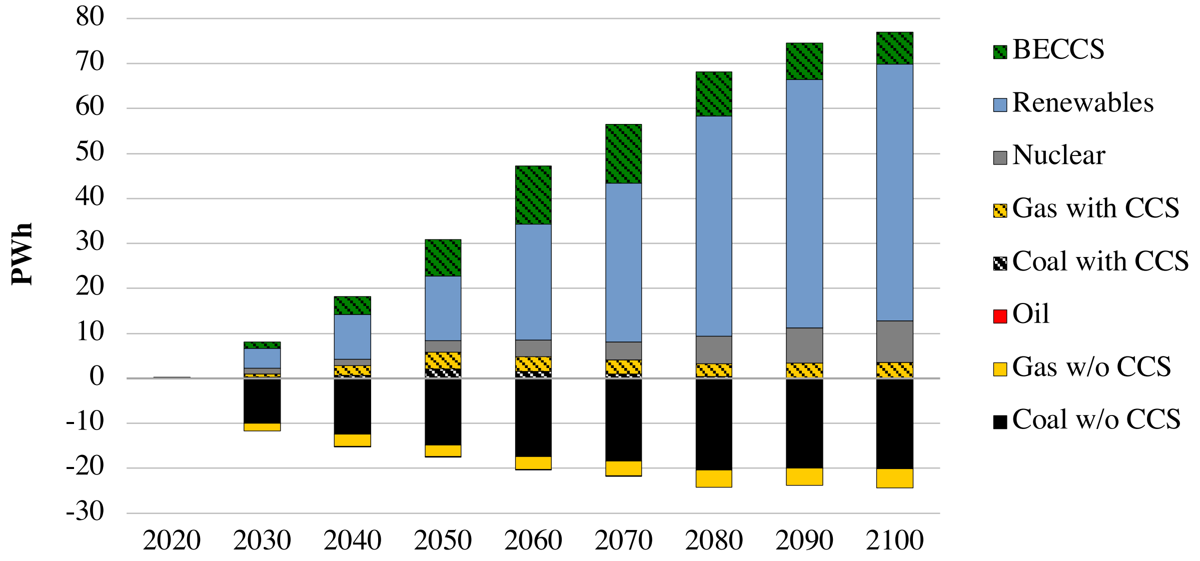


Figure 6-17: Changes in the global electricity generation mix from 2014 to 2100 in the B2D, relative to the Base

Achieving the well-below 2°C target requires USD 190 trillion of investment in power plants between 2020 and 2100. This means an increase of \$ 135 trillion (235%) over that needed in the Base (Figure 6-18). Average annual investment in the B2D is USD 2.4 trillion from 2020 to 2100, which is more than three times the electricity generation investment of 2015 (\$ 682 billion). In the B2D, investment in renewables (excluding BECCS) dominates the other measures. It accounts for more than 72% of the cumulative investment over 2020-2100, followed by BECCS (14%), nuclear (8%), and fossil fuel with CCS (4%) and fossil fuel without CCS (2%).

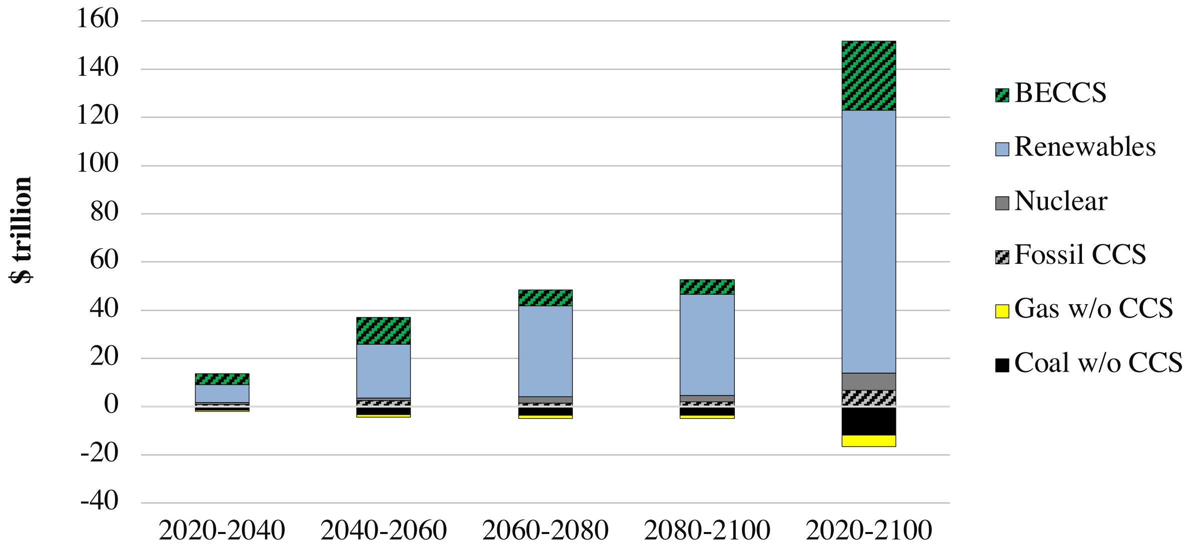
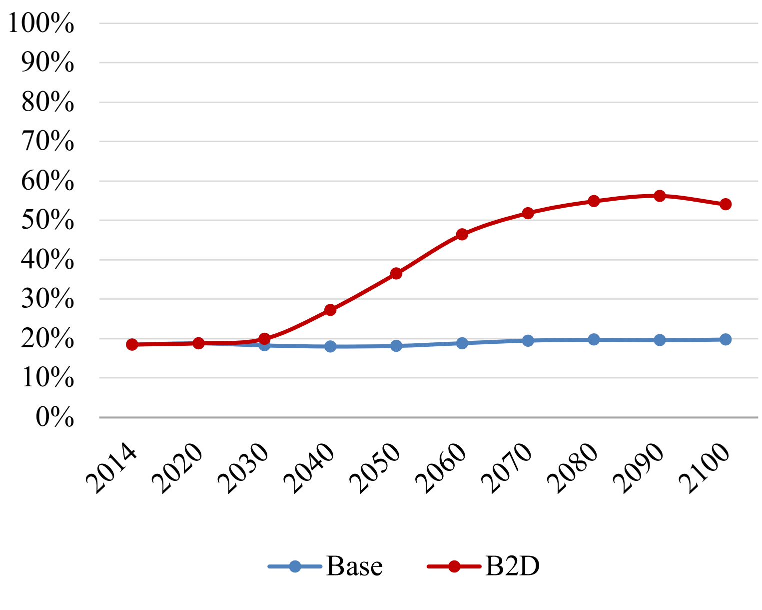


Figure 6-18: Changes in the global cumulative investments in the power sector in the B2D relative to the Base

The additional investment in the B2D compared to the Base is required not only to decarbonize the power sector, but also to meet rising electricity demand due to the vast electrification of end-uses. In essence, electrification of end-use demand facilitates decarbonization of the whole system, for two reasons: first, this sector is more flexible than other sectors (e.g., transport) in deploying zero- and low-carbon technologies. Second, electric end-use technologies are often more efficient compared to their fossil fuel alternatives. This being so, electrification can reduce overall CO_2 emissions, even if the power sector is not deeply decarbonized. For instance, if the CO_2 intensity of electricity becomes lower than 550 gCO_2/KWh, replacing a common gasoline vehicle with an electric one leads to overall CO_2 reductions (IEA, 2017).

Figure 6-19 shows that in the Base, share of electricity in the global final energy consumption (excluding non-energy consumptions) remains almost constant over the century, whereas in the B2D, it increases dramatically from 19% in 2014 to 53% in 2100. This denotes that a cost-effective strategy to reach the ambitious well-below 2°C target is decarbonizing the power sector and substituting fossil fuels in end-use sectors with the decarbonized electricity.

The Figure 6-19 also presents changes in the regional total electricity generation in the B2D compared to the Base. It highlights that China is the leading driver of higher electricity demand in the B2D scenario. However, this country is currently facing several barriers in electricity transmission capacity, which may limit future expansion of its electricity grids (REN21, 2016).



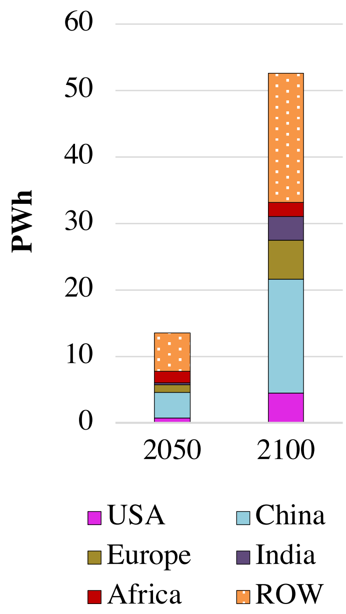


Figure 6-19: Share of electricity in global final energy demand (excluding consumptions for non-energy purposes) in the B2D and Base (left) and additional regional electricity generation in the B2D relative to the Base (right)

6.3.5 Decarbonization of the transport sector

In 2014, the transport sector accounted for 28% of total final energy demand and 23% of energy-related CO_2 emissions, worldwide. Oil is currently by far the main transportation fuel in the world. More than 94% of the global final transport energy demand in 2014 was provided by oil, followed by biofuel with 3%, natural gas with 2% and electricity with only 1%.

Figure 6-20 illustrates that total final energy consumption of the transport sector in the Base increases from 107 EJ in 2014 to 181 EJ in 2100. Oil remains the dominant transportation fuel with a share of 79% in final energy mix by 2100. In contrast, the share of biofuels in total final energy use increases to 13% in 2100, while the share of other fuel types remains almost stable. Road freight vehicles (light, commercial, medium and heavy trucks) are the main drivers for biofuels consumption in this sector. Carbon intensity of the sector falls from 69 gCO_2/MJ in 2014 to 59 gCO_2/MJ in 2100, due to the increased use of natural gas in the short term and (mainly) biofuels in the longer term. In this scenario, hydrogen, as the major fuel in the "Others" category, starts to contribute from almost 2040. This is basically due to the expected cost reduction and technology improvement in the hydrogen production processes. Heavy trucks are the main consumers of hydrogen in this scenario. Methane is the other fuel considered in the "Others" category.

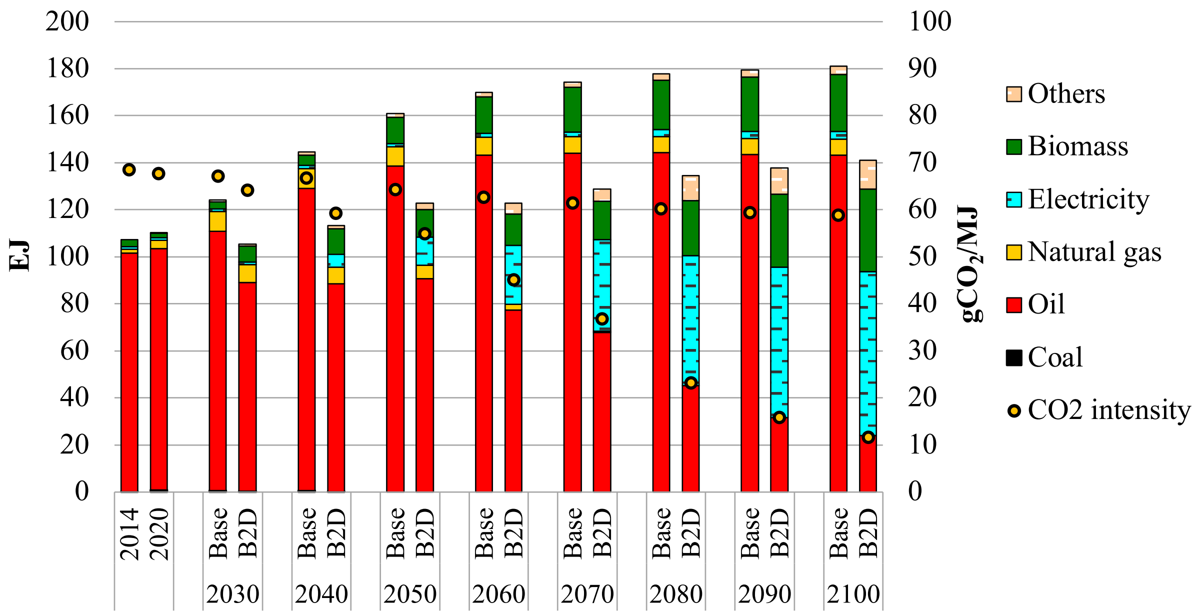


Figure 6-20: Global final energy consumption by energy carrier and CO_2 intensity[20] of the transport sector

Meeting the ambitious well-below 2°C goal implies significant transformations in each transportation mode. As presented in Figure 6-21, carbon intensity of transport in the B2D dramatically decreases to 12 gCO_2/MJ in 2100. Electricity emerges as the major transport fuel in 2100, providing almost 50% (70 EJ) of the final energy mix. In particular, electrification offers a promising decarbonization solution for rail and road subsectors. In 2100, the share of electricity in the fuel mix of rail transport and road transport is 100% and 60%, respectively. Today, roughly two-thirds of all rail transport is driven by electricity (GEA, 2012).

In the B2D, the share of biofuels increases from 3% in 2014 to 25% in 2100. Limited availability of biomass, the need for biomass consumption across other sectors and the key role

[20] CO_2 intensity of a sector refer to the direct CO_2 per unit of final energy consumption of the sector

of BECCS narrow the possibility of using a large portion of biomass resources in the transport sector. This highlights that biomass use in transport must be prioritized on modes where other mitigation measures are either limited or too costly. Navigation and aviation are two modes with limited low-carbon alternatives. Almost all the remaining oil in 2100 (24 EJ) is consumed by these subsectors. While biofuels are substantial for decarbonizing both modes, hydrogen plays an important role in the aviation subsector. In 2100, hydrogen provides 9% (12 EJ) of the global transport final energy consumption. In general, the possibility to produce hydrogen using CCS and from low-carbon primary energy source can make it a desirable energy carrier in this context.

In the B2D, final energy consumption of the transport sector grows over the period 2020-2100 but at a lower rate than in the Base scenario. Cumulative transport final energy use over 2020-2100 in the B2D is 22% lower than the Base. This denotes the critical role that energy efficiency improvements and energy-service demand reductions play to facilitate decarbonization of the sector. As depicted in the Figure 6-21, reductions are not restricted to certain transport modes and all modes should reduce their final energy use.

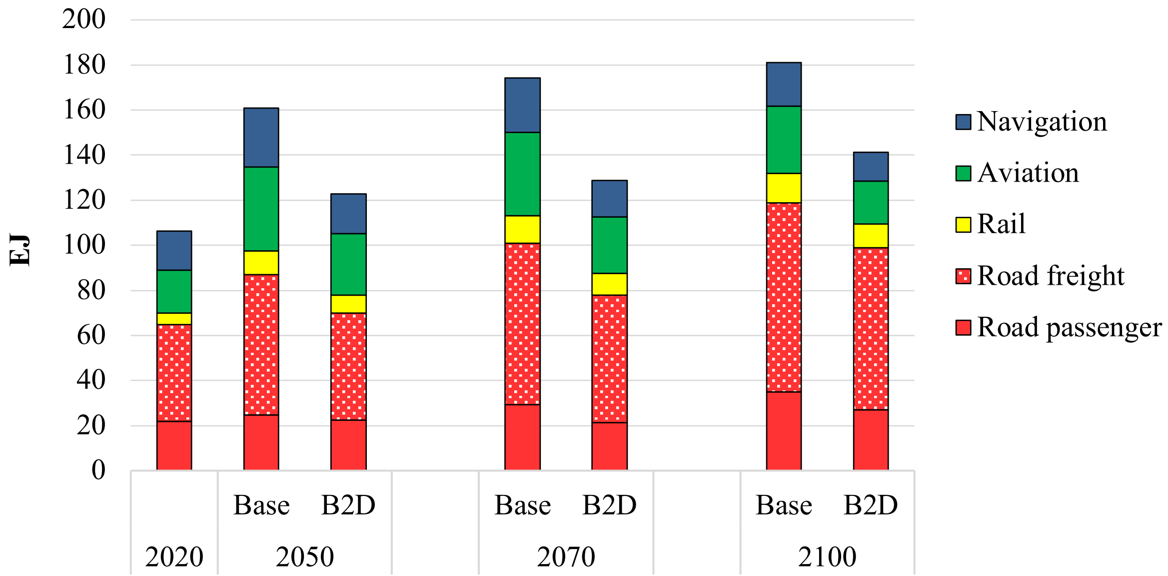


Figure 6-21: Global final energy consumption in the transport sector by mode

The major reason for lower final energy consumption by road freight and road passenger in the B2D relative to the Base is the higher energy efficiency, which is primarily explained by the much higher electrification rates in the B2D scenario. In other words, given the fact that EVs are often more efficient compared with their fossil fuel counterparts, electrification, as the main mitigation measure of road transport (including both road and passenger), improves by itself the energy efficiency of this subsector. This issue offsets the price increase in the energy services of road freight and road passenger in the B2D, leading to moderate energy-service demand reductions. In contrast, the aviation and navigation subsectors experience strong and rapid energy-service demand reductions in the B2D. In fact, as these modes have very limited low-carbon alternatives, meeting the CO_2 reduction target increases the price of their energy-services, significantly. While energy efficiency accounts for 5% of the cumulative CO_2 emissions reduction from the Base to B2D, the share of energy-service demand reductions is more than 37% (Figure 6-22). It should be emphasized that due to the vast deployment of energy efficiency measures in the Base scenario, the relatively low share of this measure does not weaken its importance in a cost-effective transition.

From Figure 6-22 it can also be observed that electricity is the main mitigation measure in the transport sector. The share of electricity is 41% in the cumulative CO_2 emissions reduction. Biomass and hydrogen have their share ramp up toward the end of the century, contributing 15% and 6%, respectively. Due to the limited use of fossil fuels in the B2D, fossil fuel switching (mainly oil to gas) represents almost 2% of the cumulative CO_2 emission reduction.

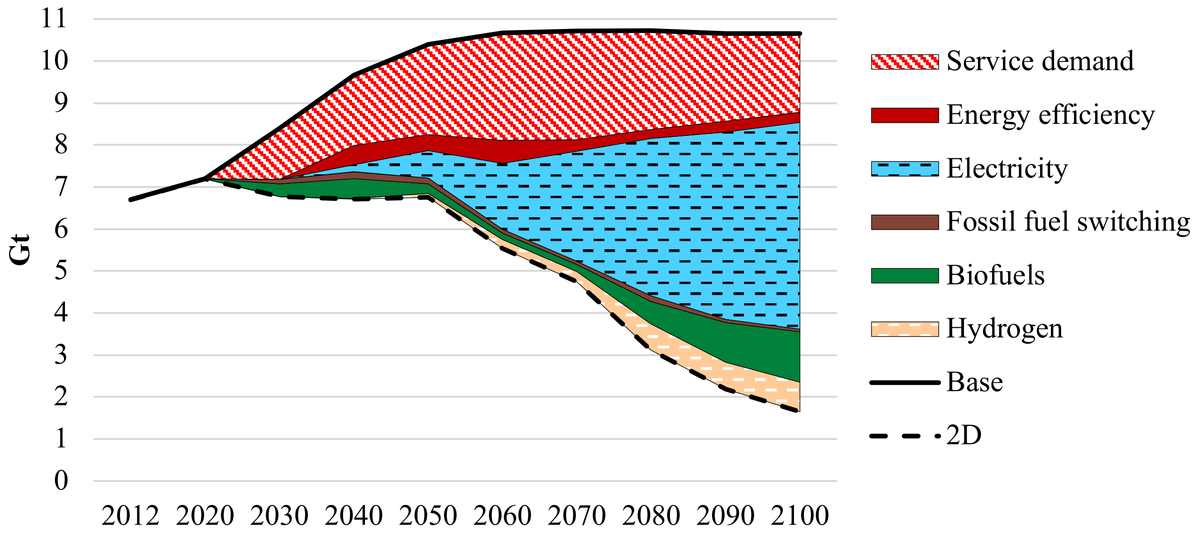


Figure 6-22: Global CO_2 emissions reductions in transport by measure, Base to B2D

6.3.6 Decarbonization of the industry sector

In 2014, the industry sector reached 129 EJ of final energy demand and 8.3 Gt of direct CO_2 emissions, which translate to a third of the world's total energy consumption and a quarter of total energy-related CO_2 emissions. Non-OECD countries accounted for a major share (71%) of the world industry final energy use. China, in particular, consumed around 38% of the world industry final energy use. The world industry sector is mainly based on fossil fuels, especially coal. In fact, 39% of industry energy need in 2014 was provided by coal, followed by electricity with 23%, natural gas with 18%, oil with 10%, biomass with 6%, and heat with 4%. In this year, CO_2 intensity of final energy use of industry was 66 gCO_2/MJ.

In the Base scenario, due to the expected population and economic growth in all world regions, final energy use in industry grows rapidly at an annual growth rate of 1.43%, reaching 439 EJ in 2100. The increase is largely fueled by increasing demand in non-OECD countries that consume 75% of world industry energy in 2100. The final energy mix in 2100 differs slightly from that in 2014. Fossil fuels continue to dominate industry energy consumption over the whole century and their share rises slightly from 66% in 2014 to 68% in 2100. In contrast, electricity's share declines from 23% to 19% in the same period. While heat consumption almost doubles by 2100, its contribution in total industry energy consumption falls to almost 1%. Moreover, the share of non-biomass renewables which are mainly used for auto-production of heat, is on par with biomass, each providing about 4% in 2100. The remainder of final energy mix in 2100 consists of other fuels (mainly hydrogen) with a share of 3%. Hydrogen is mainly consumed for direct reduced iron (DRI) process. CO_2 intensity of the sector peaks at 77 gCO_2/MJ in 2050 and then slightly declines to 73 gCO_2/MJ in 2100.

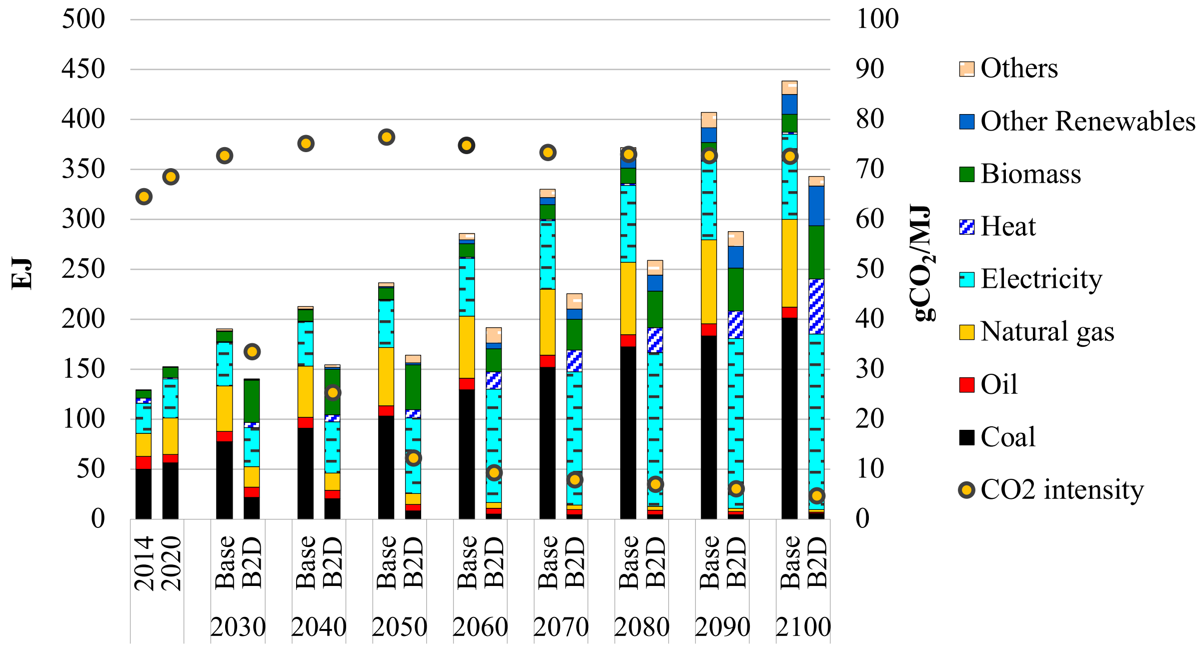


Figure 6-23: Global final energy consumption by energy carrier and CO_2 intensity of the industry sector

As reflected in Figure 6-23, meeting the ambitious target of the B2D requires remarkable and rapid changes in industry final energy mix, leading to a deep reduction in CO_2 intensity of final energy use to 5 gCO_2/MJ in 2100. In this scenario, the contribution of fossil fuels to the overall industry final energy mix should fall notably by an annual rate of 6% over the period 2020-2030 and by 2% over the post-2030 period. Given the lock-in of existing capacity, it is disputable how such a rapid and substantial reduction in fossil fuel use can be realized in practice. However, without early action, much more significant technological changes are required to reduce CO_2 emissions in the later time periods, which may increase system costs, notably. The remaining fossil fuels in 2100 (10 EJ) are used either in combination with CCS technologies or for feedstocks and non-energy purposes. This denotes that feedstock-related CO_2 emissions, and demand for petrochemical products could be challenges to a long-term ambitious mitigation transition.

Shifting energy consumption away from carbon-intensive fossil fuels is key for industry to be decarbonized. In this regard, biomass serves as an attractive alternative to fossil fuels in the short to medium term, while it plays a relatively minor role in the longer term. This is especially important given the limited availability of sustainable biomass and the necessity of using it in other sectors. In contrast, electricity and heat together, play a principal role in decarbonizing this sector, providing more than 104 EJ (67%) of final energy consumption in 2100. Given the flexibility of power system in being decarbonized, consuming electricity of a greater proportion in industry final energy use can reduce total system's emissions. This is especially evident in the post-2040.

Other renewables such as solar thermal and geothermal play a bigger role in the B2D than the Base, providing more than 11% of the total industry energy use in 2100. CCS also plays a role in a cost-effective decarbonization of the industry sector. In the B2D, cumulatively 28 $GtCO_2$ emissions are captured by fossil fuel CCS technologies in this sector. Figure 6-24 shows that of the cumulative CO_2 captured in industry, 42% occurs in China, 16% in the Middle East and 13% in the Former Soviet Union. Moreover, it depicts that annual captured CO_2 emissions increase until 2050 and decrease to a level of 116 $MtCO_2$ in 2100. In fact, due to the remaining emissions of fossil fuel CCS technologies, increasing CO_2 price in the B2D favors other mitigation technologies with lower remaining emissions. However, despite the importance of deployment of CCS in the industry sector, this measure has not yet commercially developed. Hence, a set of supportive policy frameworks are needed to address the economic and non-economic challenges of CCS deployment in industry. Such policies are especially important in the short-term to minimize current uncertainties.

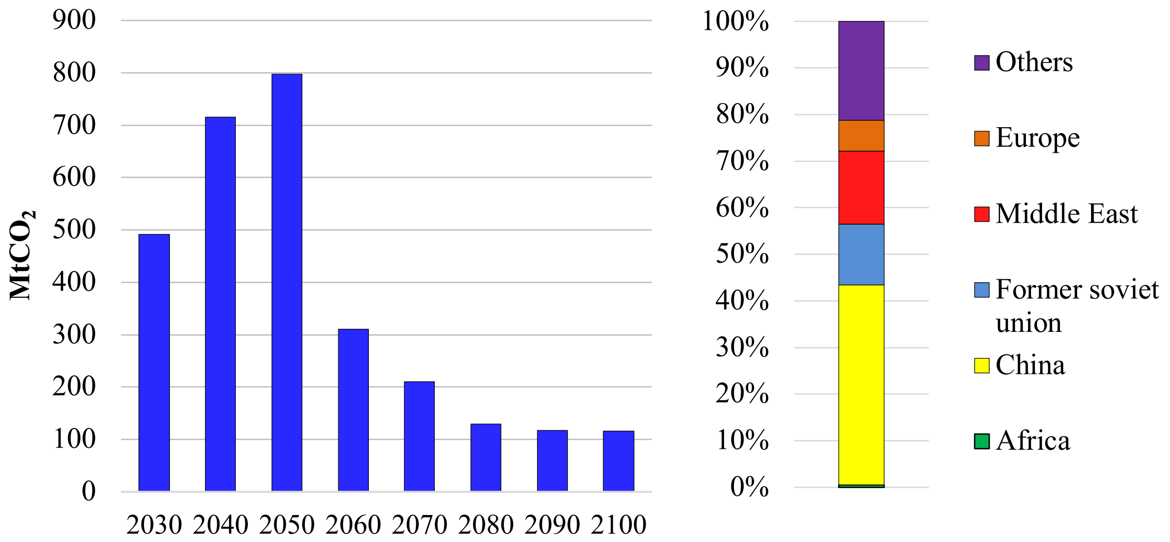


Figure 6-24: Global annual CO_2 emissions captured by CCS technologies in industry (left) and regional share of the cumulative captured CO_2 emissions in industry in the B2D

The cumulative final energy consumption of industry in the B2D is 28% lower than that in the Base. In 2030 industry final energy use in the B2D reduces by 26% relative to the Base case. A detailed look reveals that more than 70% of the reduction is caused by energy-service demand reductions. In fact, the necessity of reducing emissions on the one hand and limited availability of cost-effective mitigation measures in the short-term on the other hand, will increase the prices of energy-services, leading to energy-service demand reductions, especially in the short-term.

Figure 6-25 shows that to facilitate the decarbonization of the industry sector, all industrial subsectors (including energy-intensive and non-energy-intensive) must reduce their final energy consumption. The strongest reductions in the sectoral cumulative final energy consumption are observed in non-metallic minerals (predominately cement) with 35% and iron and steel with 26%. This highlights the key role of energy-intensive industries in the transition.

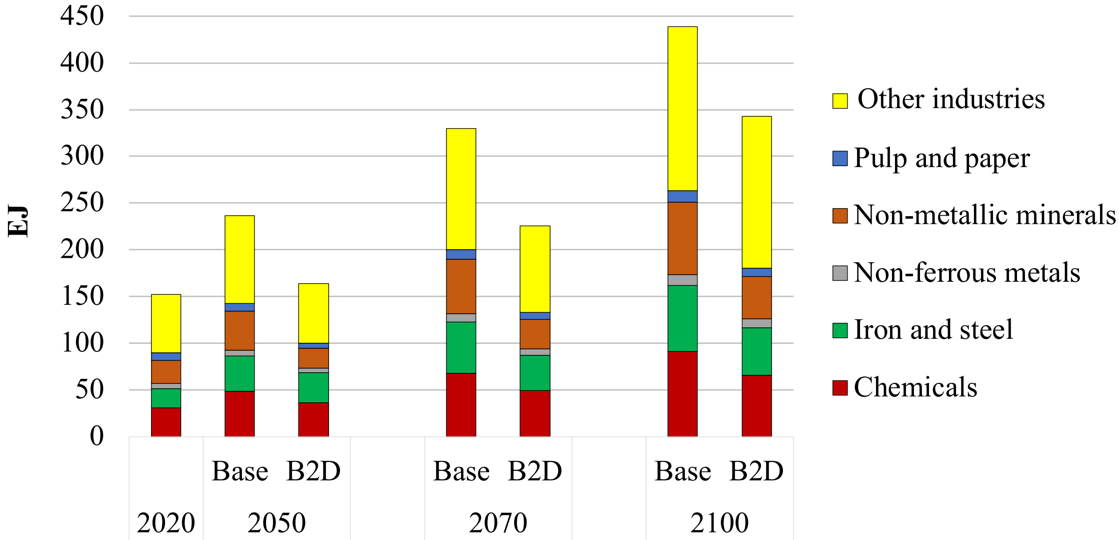


Figure 6-25: Global final energy consumption in the industry sector by subsector

Figure 6-26 shows that there are several key measures that enable the ambitious CO_2 emissions reductions in the industry sector: energy-service demand reduction, energy efficiency, electrification, heat, CCS, fossil fuel switching and deployment of renewables and hydrogen. Of the 1630 Gt cumulative direct CO_2 emissions reductions over 2020-2100, energy-service demand reduction and energy efficiency account for notable shares of 25% and 9%, respectively. It might be less of a surprise that electrification contributes the largest share (34%) in the cumulative CO_2 emissions reduction. Renewables play a substantial role with a share of 18%, followed by heat with 9%, hydrogen with 2%, CCS with 2% and switching to less carbon fossils with 1%.

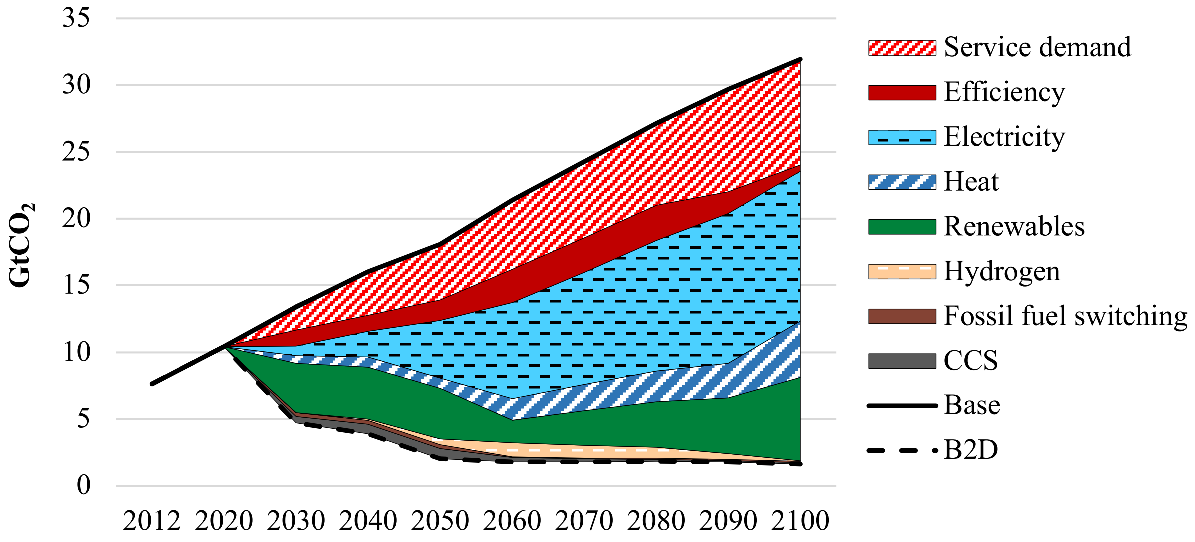


Figure 6-26: Global CO_2 emissions reductions in the industry sector by measure, from Base to B2D

6.3.7 Decarbonization of the buildings and agriculture sectors

Global buildings (i.e. residential and commercial sectors) and agriculture together consumed more than 130 EJ in 2014, which was around a third of global final energy consumption. Electricity contributed as the dominant energy source, especially in buildings, with a share of 30% in the total energy mix, followed by biomass with 23%, natural gas with 19% and oil with 17%, coal and heat, each with 5% and other renewables with around 1%. These sectors were responsible for more than 17% of global CO_2 emissions from end-use sectors.

In the Base scenario, despite the continued adoption of energy efficiency measures, especially in buildings, due to the growing income and population, final energy consumption in the buildings and agriculture sectors increases over the century at an average annual growth rate of 0.9% (Figure 6-27). In 2100, final energy consumption of these sectors reaches 280 EJ. Electricity continues to dominate final energy use and its share slightly increases to 32% by the end of the century. Oil consumption drastically falls by more than 73% in 2100 compared with 2014. To recover this reduction, natural gas and biomass use more than doubles and coal consumption more than triples over the period 2014-2100. However, in relative terms, other renewables (incl. solar and geothermal energy) experience the strongest growth to reach 34 EJ in 2100, representing 12% of the overall final energy consumption. The main driver of the higher use of other renewables is hot water and space heating demand in buildings. Last but not least, final heat consumption increases by 80% from 2014 to 2100.

In the Base scenario, global CO_2 emissions from buildings and agriculture sectors continue to rise by an annual rate of 0.6%. However, CO_2 intensity of final energy use of these sectors declines from 27 gCO_2/MJ in 2014 to 20 gCO_2/MJ in 2100.

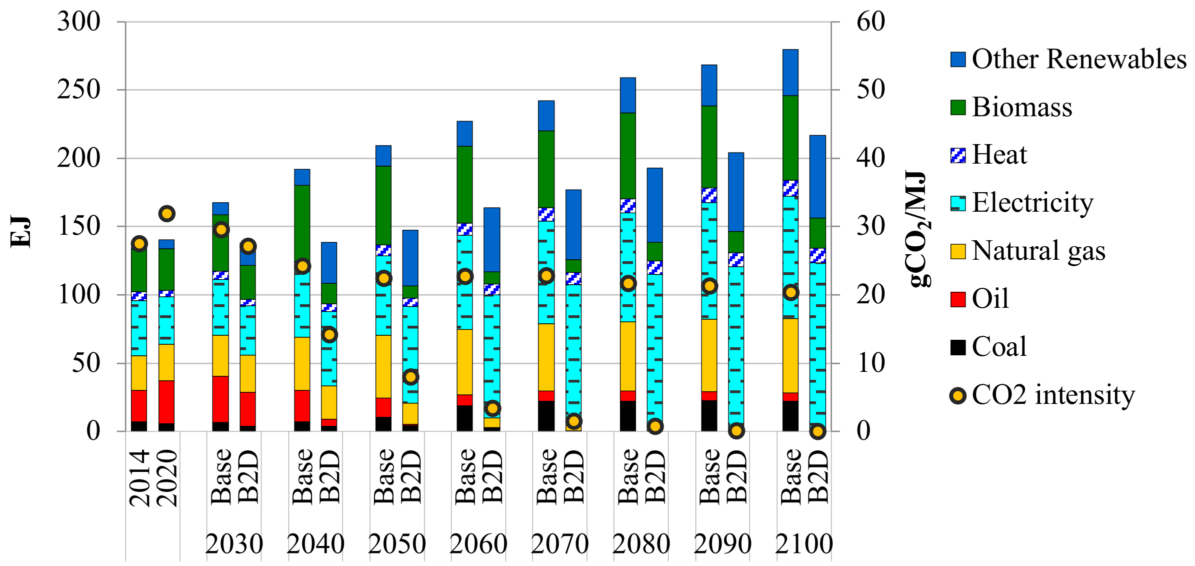


Figure 6-27: Global final energy consumption and CO_2 intensity of the buildings and agriculture sectors

In the B2D, fossil fuel use dramatically declines in the region of 7% per year to almost zero by 2100. Due to the limited availability of sustainable bioenergy resources and the urgency of biomass use in other sectors (primarily electricity and transport), biomass consumption in the agriculture and buildings sectors falls considerably by 28% between 2014 and 2100. This can be especially challenging for developing countries where over 2.5 billion people today rely on biomass to meet their cooking and heating energy need (WEO, 2006). To reduce pressure on biomass, other renewables and electricity increase their contribution substantially. Other renewables (mostly solar energy) are the main alternative for hot water, supplying around 28% of the overall final energy use in 2100. Electricity, as the major substitute for biomass in cooking and space heating in buildings, provides 57% (90 EJ) of the overall final energy use in 2100.

Figure 6-27 also reveals that in the B2D, the overall final energy consumption in the agriculture and buildings sectors slightly falls between 2020 and 2030, and increases over the post-2030 period but at a notably lower annual rate (0.7%) compared to the Base, due to more extensive adoption of energy efficiency measures and reducing energy-service demands.

Figure 6-28 shows that to facilitate the transition all sub-sectors must reduce their final energy use. Decarbonization of the agriculture sector is mainly through electrification which requires structural changes in the sector. As a result, in this scenario, the price of the energy-service of this sector experiences a notable increase. As a result, energy-service demand reductions are found to be the major reason for the observed reduction in the overall final energy use of this sector. In contrast, reduction in final energy use of buildings is mainly derived from energy efficiency improvements. In fact, while the cumulative energy-service demand of buildings over the period 2020-2100 in the B2D is 10% lower than that in the Base, the cumulative final energy consumption of this sector over the same period in the B2D is more than 24%

lower than that in the Base. In particular, heating and lighting offer a substantial potential for energy efficiency improvement that are untapped in the Base scenario.

On the other hand, since the deployment of more efficient lighting, cooling, heating and electric appliances in the B2D saves a considerable amount of electricity consumption by buildings, it allows greater electrification in the sectors with limited mitigation measures (e.g. transport), without additional pressure on the power sector.

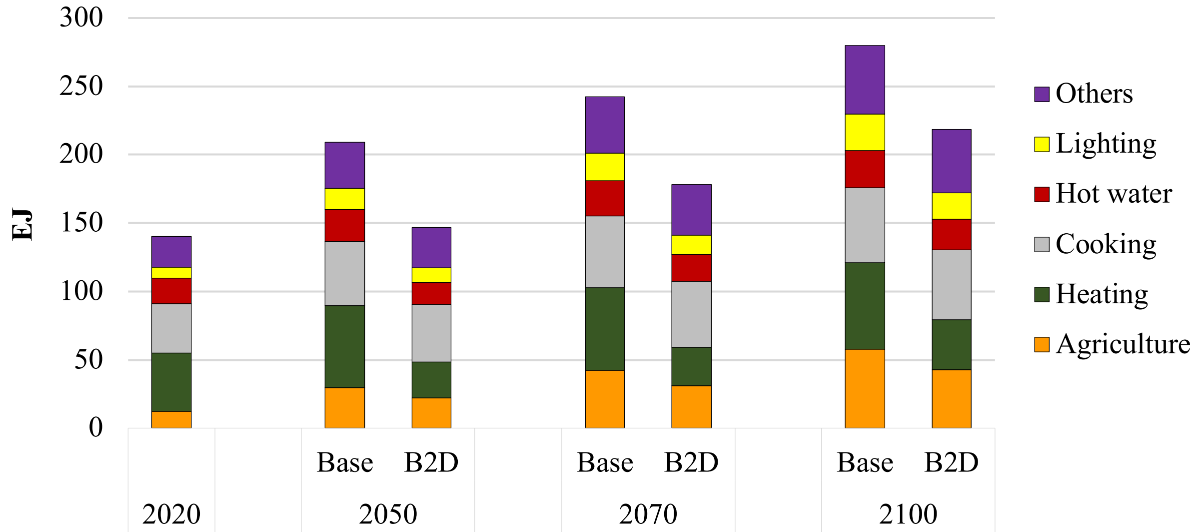


Figure 6-28: Global final energy consumption of buildings and agriculture by service demand

Figure 6-29 shows that energy efficiency is one of the largest contributors to the cumulative CO_2 emissions reduction in the shift from Base to B2D, at 19%. While energy-service demand reductions play an important role with a share of 14%, electricity is found to be the major contributor, accounting for more than 60% of the cumulative CO_2 emissions reduction. Renewables (4%) and fossil fuel switching (3%) provide the remainder emissions reduction in the push from the Base to the B2D.

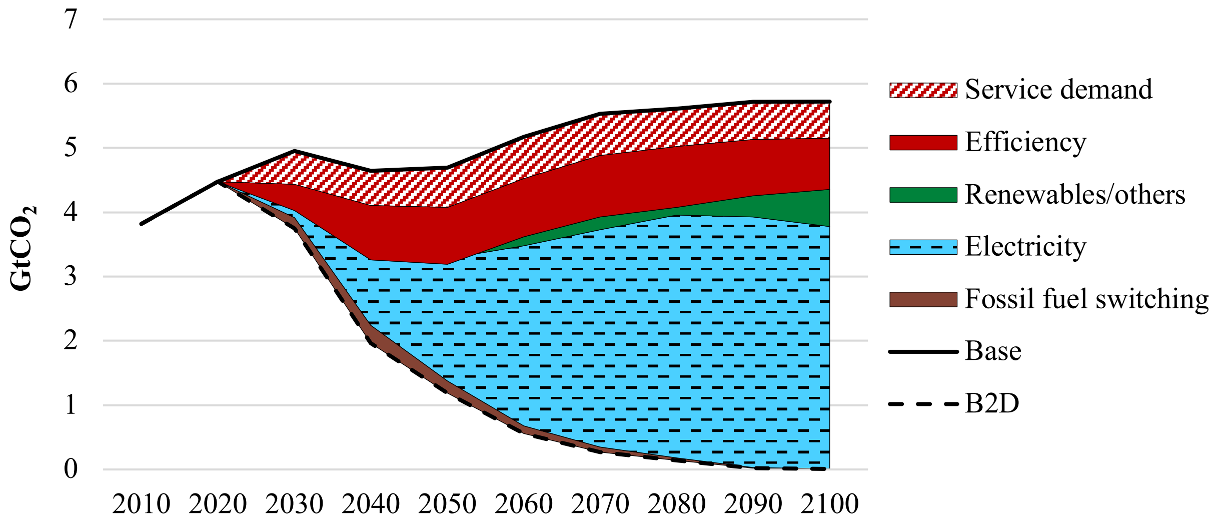


Figure 6-29: Global CO_2 emissions reductions in the agriculture and buildings sectors by measure, from Base to B2D

6.3.8 Macroeconomic implications of the decarbonization policy

For a more comprehensive and integrated assessment of a decarbonization policy, it is of crucial importance to move beyond the energy system boundaries and analyze macroeconomic implications of the policy. To evaluate such impacts on a region/country, a widely-used measure is GDP loss representing the difference in GDP of that region/country between the Base scenario and the decarbonization scenario. In fact, in the mitigation scenario, GDP would be lower than in the Base because of higher energy and emissions mitigation costs, as well as changes in resource allocation. To show the implications at the global level, here we use gross world product (GWP) loss.

Figure 6-30 shows annual GWP loss in the B2D, relative to the Base. The cumulative GWP over the period 2020-2100 in the B2D is 3.5% lower than that in the Base. This clearly denotes that despite the optimized deployment of supply-side and demand-side measures, reaching the well-below 2°C objective comes with considerable negative macroeconomic impacts. It is interesting to note that immediately after the CO_2 reduction policy is tightened, GWP experiences a substantial decline. In 2030, GWP loss in the B2D is around 2.3%. This occurs due to the extensive uptake of mitigation measures in the short-term, implying high additional costs to the energy system.

On the other hand, by looking at Figure 6-30 it can be observed that annual GWP loss in the B2D increases until 2060 and then decreases over the rest of the century. In fact, the urgency of reaching carbon-neutrality in around 2065 along with the limited availability of technological mitigation measures in the early periods impose huge negative impacts on the global economy. However, once the global energy system reaches net zero carbon, the higher availability of cost-effective mitigation measures in the later periods offsets the macroeconomic implications of the decarbonization policy.

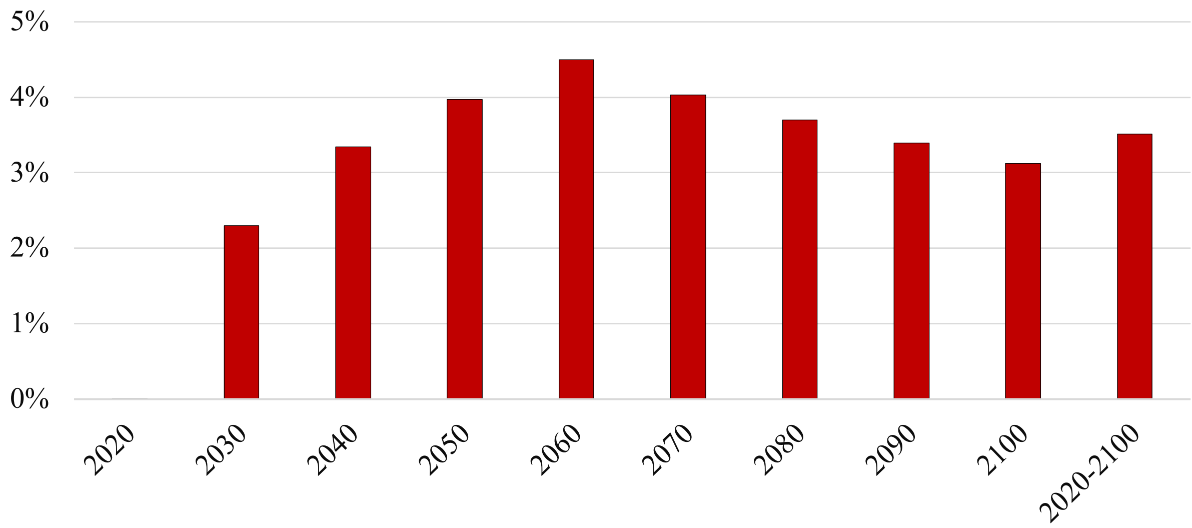


Figure 6-30: Annual and cumulative GWP loss (%) in the B2D relative to the Base

To provide a more detailed analysis, Figure 6-31 depicts regional annual GDP losses in the B2D, relative to the Base. It can be observed that the mitigation policy offsets GDP growth of all regions. However, losses are more pronounced for fossil fuel producing regions whose economies will rely heavily on fossil fuels. This is especially the case for China and Former Soviet Union as they suffer the most with 6.2% and 6.3% loss in their cumulative GDP over 2020-2100, respectively.

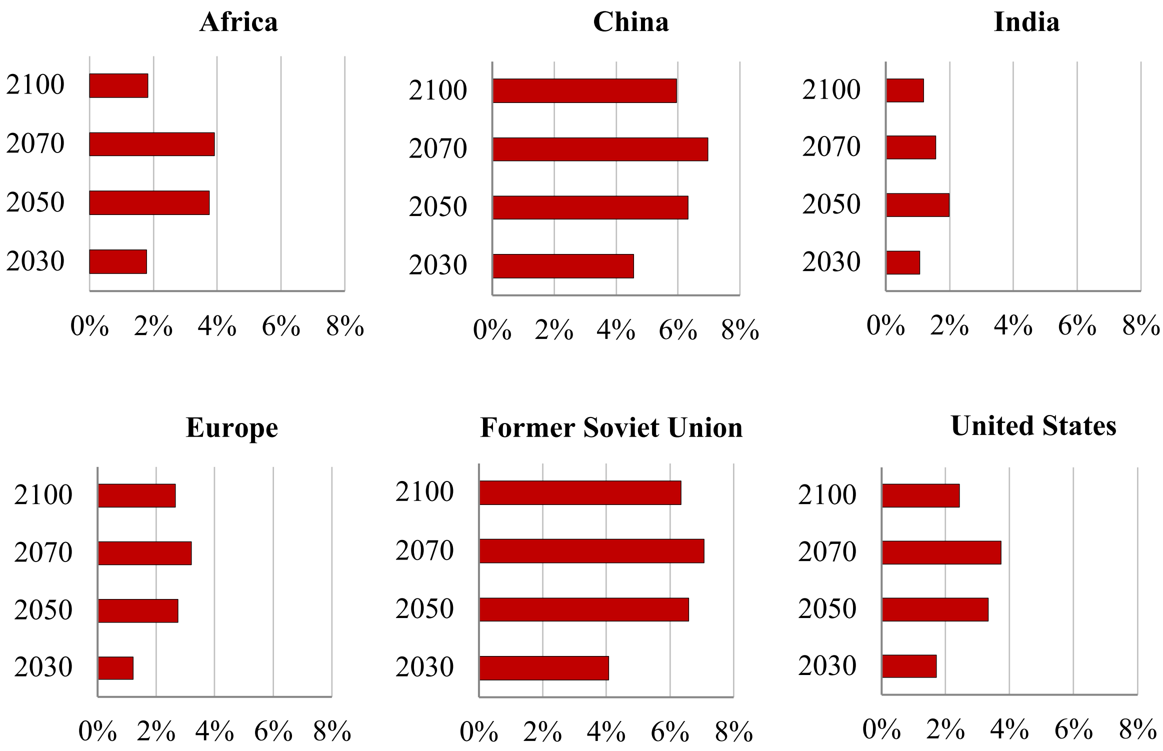


Figure 6-31: Annual GDP Losses (%) in the B2D relative to the Base by region

6.3.9 Role of non-biomass renewables potential

It has been found that non-biomass renewables are key actors in the shift from the Base to B2D. This section investigates the role that increasing the technical and the yearly realizable potentials for non-biomass renewables play in shaping the global mitigation pathway toward the well-below 2°C target. To this end, the B2D is compared with the B2D+REN which assumes 25% higher potential for non-biomass renewables.

Figure 6-32 reveals that the additional potential for non-biomass renewables does not lead to a significant change in the overall use of these sources, especially in the long-term. In fact, the necessity of reaching carbon-neutrality in the global energy system by around 2065 requires massive deployment of zero-carbon sources in the short to medium term, when the realizable potential for non-biomass renewables is limited (Figure 6-3). Hence, the additional realizable potential in the short to medium term facilitates the decarbonization. In 2040, the annual consumption of non-biomass renewables in the B2D+REN is 8% higher than in the B2D. However, in the very long-term when the high technical potentials can be utilized (Figure 6-3), the additional potentials do not result in notably higher deployment of renewables. From the global perspective, the technical potential of non-biomass renewables more than doubles the total primary energy consumption of the B2D in 2100. In particular, the technical potential of solar energy (1200 EJ) is higher than the global primary energy consumption of the B2D scenario in 2100 (1085 EJ).

Figure 6-32 also shows that regardless of the potential for non-biomass renewables, an optimized pathway to well-below 2°C requires a noticeable contribution of hydro, geothermal, wind and solar resources. However, it can be observed that despite the great potential for ocean energy, its penetration in both scenarios is limited to a share of less than 1% of the cumulative primary energy mix.

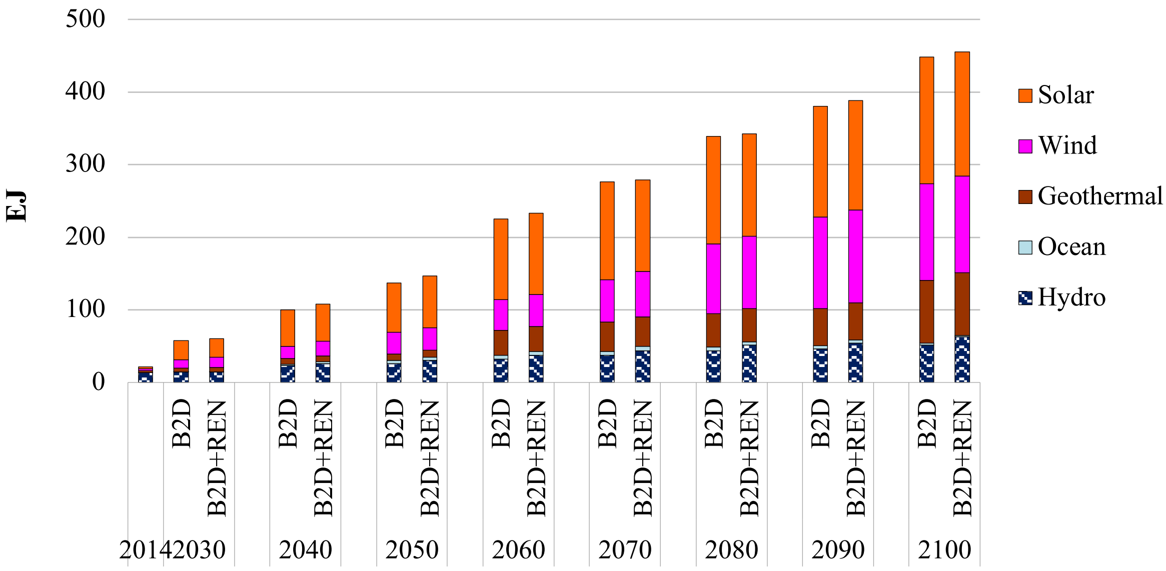


Figure 6-32: Global annual primary energy consumption of non-biomass renewables in the B2D and the B2D+REN

Table 6-12 shows that the share of renewables in the cumulative CO_2 reduction from the Base to the well-below 2°C slightly increases from 42% in the B2D to 43% in the B2D+REN. The additional potential for non-biomass renewables offsets the increase in energy-service demands prices. As a result, the share of energy-service demand reductions slightly declines from 22% in the B2D to 21% in the B2D+REN.

Table 6-12: Relative roles of mitigation measures (%) in cumulative CO_2 reduction in the B2D and B2D+REN

	Service-demand	Efficiency	Renewa-bles	Nuclear	Fossil fuel switching	Fossil fuel CCS	BECCS
B2D	22	1	42	14	3	7	11
B2D+REN	21	1	43	14	4	6	11

In order to provide more insight into the role of potential for non-biomass renewables, Figure 6-33 illustrates the changes in annual global primary energy consumption of each of the non-biomass renewables in the B2D+REN relative to the B2D. As discussed, in the B2D+REN, the overall annual primary non-biomass renewables consumption in the period 2070-2100 is only slightly higher than the B2D.

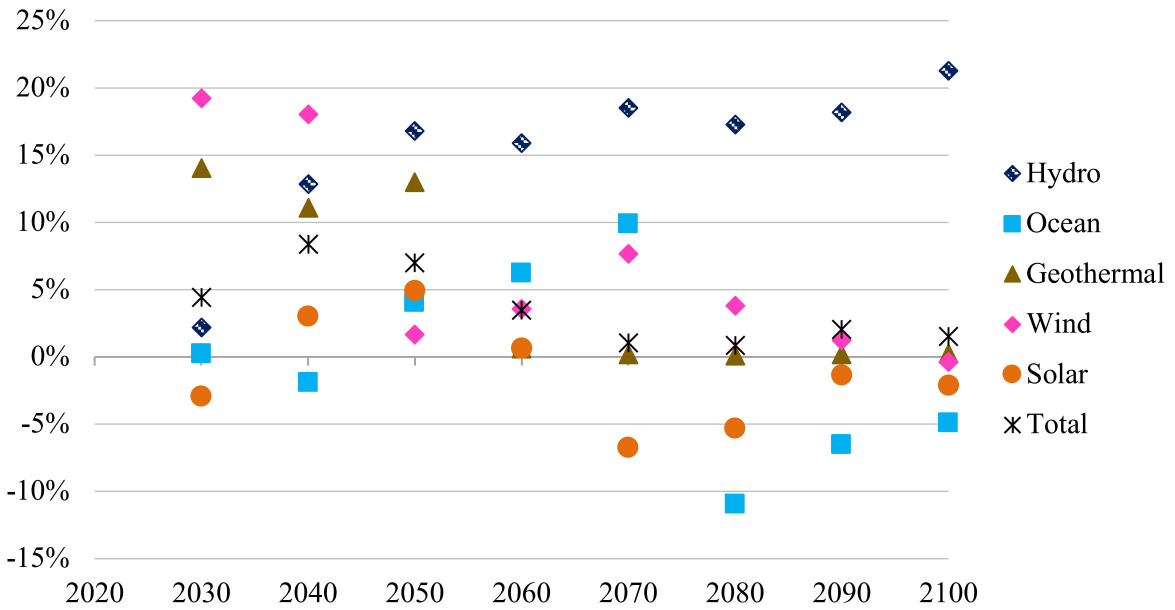


Figure 6-33: Changes in annual global primary energy consumption of non-biomass renewables in the B2D+REN, relative to the B2D

The figure presents the complementary role of renewables. In the short-term, greater potential for geothermal and wind in the B2D+REN increases the penetration of these two resources and offsets the contribution of solar energy. In 2030, geothermal and wind represent 14% and 19% higher contribution, respectively, while solar is 3% lower in the B2D+REN compared to the B2D. While in the initial periods, the use of geothermal in the B2D+REN is noticeably higher than the B2D, from 2060 to 2100, it follows almost the same path in both scenarios.

From 2040 onwards, hydro demonstrates a significant increase in the B2D+REN compared to the B2D. In 2100, consumption of hydro in the B2D+REN is more than 20% higher than that in the B2D. Besides reducing total system cost, higher potential for hydropower increases the flexibility of electricity supply, which is critical to accommodate and facilitate growth of variable renewables. In the long-term, the more extensive use of hydropower reduces the deployment of solar and ocean resources in the B2D+REN compared to the B2D.

Table 6-13 shows that the additional potential for non-biomass renewables can recover some of the GWP losses caused by the climate policy. It can be observed that the additional potential has a bigger role in the short to medium term, then in the long-term. In the B2D, the loss in the cumulative GWP over 2020-2100 is 3.5%, while this in the B2D+REN is 3.4%. This means that each PJ of the additional potential saves around 2.4 thousand dollars of the cumulative GWP.

Table 6-13: Annual and cumulative GWP losses (%) in the B2D and the B2D+REN, relative to the Base

	2030	2040	2050	2060	2070	2080	2090	2100	2020-2100
B2D	2.3	3.3	4.0	4.5	4.0	3.7	3.4	3.1	3.5
B2D+REN	2.2	3.1	3.8	4.3	3.9	3.6	3.3	3.0	3.4

6.3.10 Role of carbon storage potential

Considering uncertainty surrounding the capacity of the available geological carbon storages, this section explores the impacts of expanding carbon storage potential on the role that CCS plays in meeting the ambition. To this end, the B2D is compared with the B2D+CCS which assumes 25% higher carbon storage potential.

CCS has experienced significant successes in recent years. Nevertheless, it currently plays virtually a small role in the global energy system. According to IEA (2017), the number of large-scale CCS projects in operation has increased to 17 in 2017, capturing around than 30 $MtCO_2$ per year globally.

Similar to the B2D, in the B2D+CCS scenario which benefits from 25% higher potential of CO_2 storage potential, CCS is applied to coal, gas and bioenergy to reduce emissions from fuel production and transformation, industrial processes and power generation. Both scenarios requires significant deployment of CCS technologies in the short-term. In 2030, the CO_2 emissions captured by CCS technologies are around 1.8 $GtCO_2$ in the B2D and 2.3 $GtCO_2$ in the B2D+CCS.

Cumulatively, in the B2D, over 629 $GtCO_2$ are captured and stored between 2015 and 2100, while in the B2D+CCS captured CO_2 emissions increases by 18%, reaching 741 $GtCO_2$. Table 6-14 presents the ratio of stored CO_2 emissions to the storage potential in different regions. According to this table, to pursuit effort toward a well-below 2°C target, CCS is needed to be implemented extensively in all world regions. However, a majority of current CCS projects are in regions (e.g., United States) where CO_2 storages are easily accessible. Furthermore, it can be seen that under both scenarios, only in a few regions (i.e., Former Soviet Union, Middle-East) the full potentials for CO_2 storages are not deployed. Therefore, it can be concluded that in most of the world regions, the effectiveness of CCS relies on the accessibility and capacity of CO_2 storage resources.

Although the electricity sector is more flexible in deploying low-carbon technologies than the other two (i.e., industry and transformation), in both scenarios, CO_2 emissions are mostly captured by CCS technologies in the power sector (Figure 6-34). In the B2D+CCS, the cumulative amount of CO_2 sequestrated by CCS in the power sector is around 645 $GtCO_2$, meaning 21% more than that in the B2D. As it is already pointed out, due to the need to make electricity generation a carbon-negative source, BECCS plays a central role in the power sector. In the

B2D+CCS, the cumulative CO_2 emissions captured by BECCS in the B2D+CCS are 14% higher than the B2D. It is interesting to note that although rising carbon price decreases the attractiveness of fossil fuel generation with CCS, higher carbon storage potential in the B2D+CCS leads to relatively more extensive use of these technologies in the power sector. The cumulative CO_2 sequestrated by fossil fuel power plants with CCS in the B2D+CCS is almost 50% higher than the B2D. In addition to generating low-carbon electricity, CCS technologies benefit the power sector by providing more balancing capacity to enable growing penetration of variable renewables. However, despite the higher potential of CO_2 storage in the B2D+CCS, coal power plants with CCS are phased out at around 2080. This is due to the relatively high residual emissions emitted from such power plants.

Table 6-14: The level of stored CO_2 emissions, CO_2 storage potential and the ratio of the stored CO_2 to the storage potential in different world regions in the B2D and B2D+CCS

	B2D			**B2D+CCS**		
	Stored CO_2 ($GtCO_2$)	**CO_2 storage potential ($GtCO_2$)**	**Ratio (%)**	**Stored CO_2 ($GtCO_2$)**	**CO_2 storage potential ($GtCO_2$)**	**Ratio (%)**
Africa	67	67	100	84	84	100
Australia	49	49	100	62	62	100
China	160	160	100	200	200	100
Europe	55	55	100	68	68	100
Former Soviet Union	69	127	55	73	159	46
India	18	18	100	23	23	100
Middle East	36	103	35	31	129	24
United States	46	46	100	58	58	100
Others	122	176	100	142	153	95

As earlier discussed, CCS is one of the mitigation options available in the industry sector. Although it plays an important role in the first half of the century, in the latter half its contribution to the overall CO_2 emissions reductions in this sector is not that significant. As explained above, this is because of remaining untapped emissions from fossil fuel CCS technologies that make them unattractive, especially after around 2060 due to the need for reaching a net zero-carbon energy system. However, as it is presented in Figure 6-34, increasing the carbon storage potential leads to greater cumulative amount of CO_2 captured from industrial processes. Quantitatively speaking, in the B2D+CCS, over 31 $GtCO_2$ of cumulative CO_2 emissions are captured in the industry sector, representing 8% higher than that in the B2D.

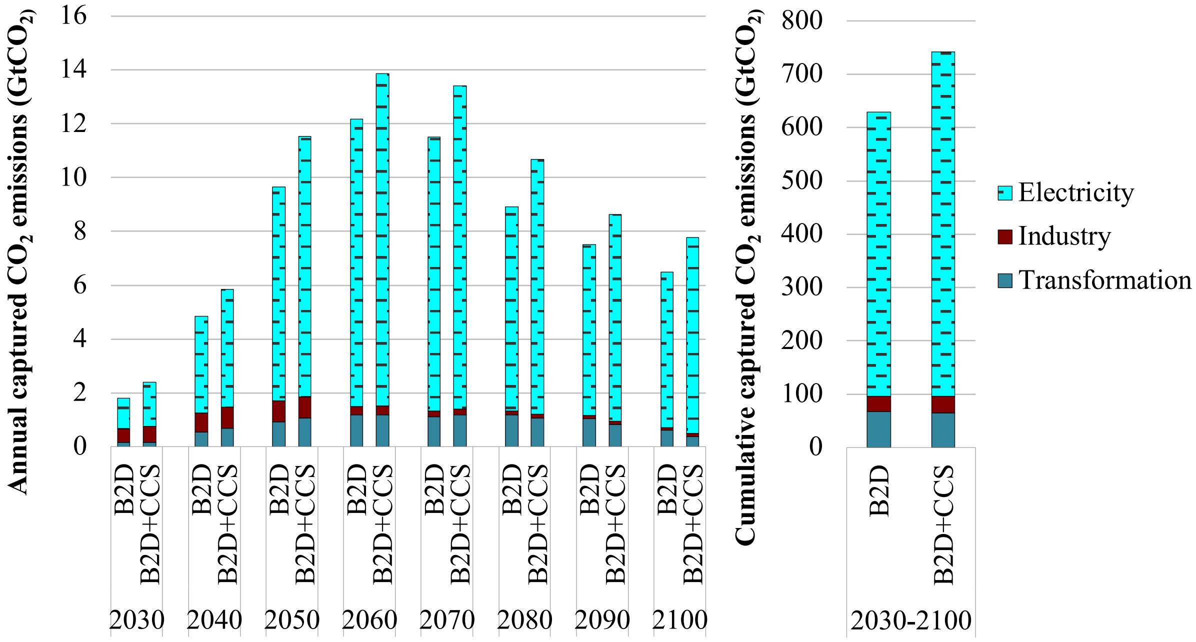


Figure 6-34: Annual and cumulative CO_2 emissions captured by CCS in different sectors in the B2D and the B2D+CCS

In the fuel production and transformation, CCS is mostly used for biofuel production and hydrogen production from natural gas and bioenergy. Due to the fact that the CO_2 separation is often an inherent part of the hydrogen production from natural gas, CCS is widely applied to this process. In the B2D, more than 55% of the cumulative CO_2 captured in fuel transformation is derived from hydrogen production from natural gas. Despite this, the cumulative CO_2 captured in fuel transformation in the B2D+CCS is around 3% lower than that in the B2D. This shows that more extensive use of CCS in the other sectors reduces the urgency of decarbonizing the fuel transformation sector, especially in the last three decades of the century.

From another perspective, Figure 6-35 shows CCS technologies by energy carrier in the B2D and the B2D+CCS. It is observed that CCS is mostly applied to biomass technologies in the power and fuel production/transformation sectors. Around 70% of the cumulative CO_2 captured is derived from BECCS, followed by natural gas with CCS (20%) and coal with CCS (10%). The increase in the carbon storage potential leads to higher penetration of both fossil fuel and biomass with CCS technologies. However, despite the critical role of BECCS in decarbonizing the whole energy system, the cumulative CO_2 captured by BECCS in the B2D+CCS is only 12% higher than the B2D. There are two explanations for this issue. First, BECCS is already deployed in the B2D scenario to a large extent. Second, the availability of sustainable bioenergy in the B2D+CCS is limited in the same way as in the B2D. In contrast to BECCS, the potential for CO_2 storage substantially increases the penetration of fossil fuel CCS technologies. The cumulative CO_2 captured by coal with CCS and natural gas with CCS in the B2D+CCS is around 46% and 22% higher than the B2D, respectively.

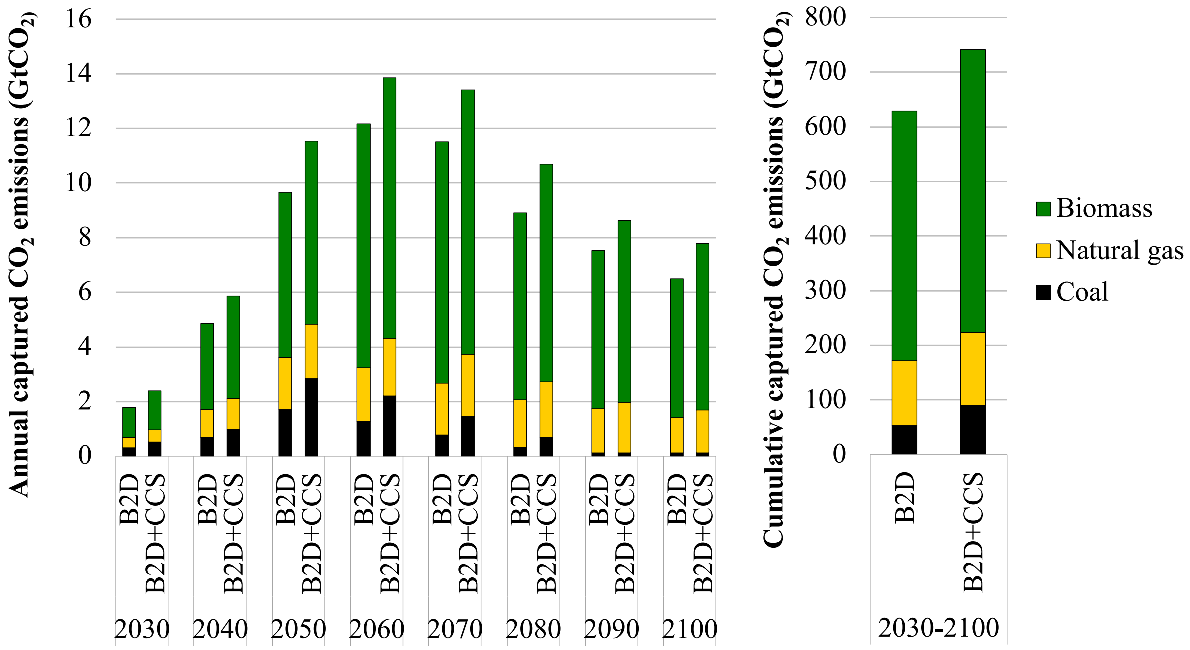


Figure 6-35: Annual and cumulative CO_2 emissions reductions from different CCS technologies in the B2D and B2D+CCS

The additional potential for carbon storages offsets the increase in price of energy-services. As a result, the contribution of energy-service demand reductions declines in the B2D+CCS. Table 6-15 reflects that the role of energy-service demands in the cumulative CO_2 emissions reduction from the Base to the well-below 2°C decreases from 22% in the B2D to 20% in the B2D+CCS. In addition, the higher potential in the B2D+CCS reduces the pressure on renewables in the B2D+CCS, contributing 2% lower than in the B2D.

Table 6-15: Relative roles of mitigation measures (%) in cumulative CO_2 reduction in the B2D and B2D+CCS

	Service-demand	Efficiency	Renewables	Nuclear	Fossil fuel switching	Fossil fuel CCS	BECCS
B2D	22	1	42	14	3	7	11
B2D+CCS	20	1	40	14	4	9	13

From a macroeconomic perspective, Table 6-16 presents that increasing the potential for carbon storage sites in the B2D+CCS recovers some of the GWP losses caused by the climate mitigation policy. While in the B2D, the loss in the cumulative GWP over 2020-2100 is 3.5%, this in the B2D+CCS is 3.3%. This means that each Gt of the additional global carbon storage saves more than 350 million dollars of the cumulative GWP.

It is noteworthy that expanding the potential for carbon storage not only benefits the regions that have substantial storage resources, but also ensures a more cost-effective transition for other regions through the purchase of lower-cost emissions credits made by higher CCS deployment in some regions. However, fossil fuel-rich countries benefit the most from the additional storage potential. Such regions can likely rely more on a broader mix of fuels to power their economies. The cumulative GDP loss in Middle-East in the B2D is 3.9%, while this in the B2D+CCS is 3.4%.

Table 6-16: Annual GWP losses (%) in the B2D and the B2D+CCS, relative to the Base

	2030	2040	2050	2060	2070	2080	2090	2100	2020-2100
B2D	2.3	3.3	4.0	4.5	4.0	3.7	3.4	3.1	3.5
B2D+CCS	2.2	3.3	3.8	4.3	3.8	3.5	3.2	2.9	3.3

6.3.11 Role of biomass potential

Biomass is currently by far the leading renewable resource in the global primary energy mix. In 2014, it accounted for 10% (55 EJ) of the overall global energy consumption. As previously identified, it will play a vital role in meeting the well-below 2°C target. However, due to the uncertainty around the potential for sustainable biomass resources, this section focuses on the impacts of rising biomass potential on the contribution of different biomass-based technologies in moving toward the decarbonization ambition. In this regard, the B2D scenario is compared with the B2D+BIO that assumes 25% higher potential for biomass resources.

The cumulative bioenergy consumption over the period 2020-2100 in the B2D+BIO is almost 25% higher than the B2D. This clearly highlights the significance of the availability of sustainable biomass resources in meeting ambitious mitigation targets. However, to provide a more detailed assessment, bioenergy consumption by different sectors in these scenarios is discussed here.

Buildings are currently the largest consumer of biomass. In 2014, this sector was responsible for more than 55% of total biomass consumption in the energy sector. However, to meet the B2D objectives, traditional use of bioenergy in buildings should be radically declined. This is especially the case for emerging countries where bioenergy is extensively used for cooking and heating services. In the B2D, final biomass consumption by buildings declines substantially from 31 EJ in 2014 to around 20 EJ in 2100 (Figure 6-36). However, increasing the potential for biomass in the B2D+BIO leads to a considerable increase in its consumption by buildings, reaching 43 EJ in 2100. Cumulative biomass consumption by this sector in the B2D+BIO over the period 2020-2100 is surprisingly around 50% higher than that in the B2D. Due to the restricted availability of biomass in the B2D, its use is notably shifted from buildings to more critical sectors (e.g., transport) where limited low-carbon alternatives exist. However, increasing the potential in the B2D+BIO provides higher flexibility to the already fully decarbonized energy system to reduce mitigation costs of the buildings sector.

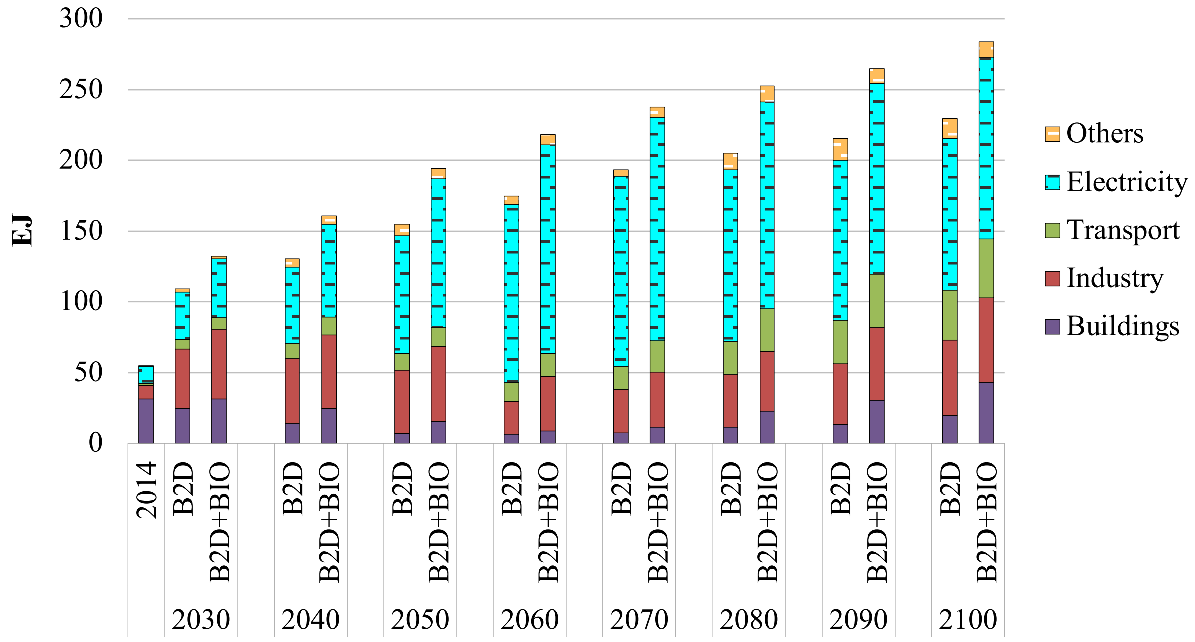


Figure 6-36: Annual final consumption of biomass by end-use sector in the B2D and B2D+BIO

According to Figure 6-36, soon after mitigation policy is tightened, the power sector overtakes buildings to be the largest consumer of bioenergy. In the B2D, more than 56% of the cumulative biomass consumption over the period 2020-2100 occurs in this sector. Although this share in the B2D+BIO falls negligibly to 54%, the cumulative biomass consumption by the power sector in this scenario is 20% higher that the B2D. Despite the importance of BECCS, Figure 6-37 shows that only around one third of the cumulative additional biomass in the power sector over the period 2020-2100 is used by this type of power plants. This, in combination with the previous findings of the chapter, points out that the deployment of BECCS not only depends on the availability of sustainable biomass but also relies on the potential for carbon storage resources.

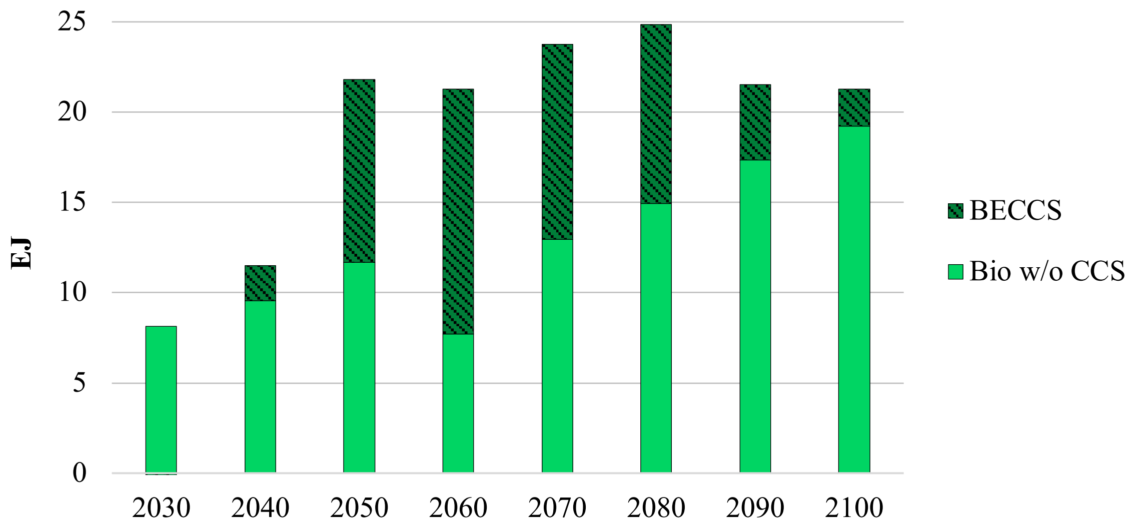


Figure 6-37: Annual additional biomass consumption in the power sector with and without CCS in the B2D+BIO, relative to the B2D

Meeting the well-below 2°C ambition implies an expanded role for bioenergy in a broad range of industrial subsectors, mainly for producing steam and heat. In most of the sub-sectors bioenergy is used extensively as a low-carbon substitute for fossil fuels. In both scenarios, the industry sector accounts for around 23% of the cumulative bioenergy consumption. However, in the B2D+BIO, the cumulative bioenergy consumption in industry is 20% higher than the B2D.

The transport sector requires a substantial departure from its current energy mix to be in line with the decarbonization target. In addition to large-scale deployment of EVs, this sector needs to adopt significant shares of biofuels. In the B2D, about 11% of the cumulative biomass consumption over the period 2020-2100 is directly consumed in this sector. In the B2D+BIO, this share is almost the same as in the B2D, while the sector consumes 23% more biofuels than in the B2D, cumulatively.

Agriculture which is decarbonized mainly through electrification, consumes only small quantities of biomass in the B2D scenario. In the B2D+BIO, the increase in cumulative biomass use by agriculture compared to the B2D is limited to less than 5%.

On the other hand, the additional biomass supply reduces the price of energy-services, which offsets the contribution of energy-service demand reductions. Table 6-17 presents that the share of energy-service demand reductions in the cumulative CO_2 reduction declines from 22% in the B2D to 19% in the B2D+BIO. This once more illustrates the importance of sustainable biomass supply in a cost-effective transition. Moreover, the table shows that the overall contribution of fossil fuel CCS measure reduces from 7% in the B2D to 5% in the B2D+BIO. As discussed, this is primarily due to fact that the use of BECCS not only depends on the availability of sustainable bioenergy supply, but also relies on the potential for CO_2 storage.

Table 6-17: Relative roles of mitigation measures (%) in cumulative CO_2 reduction in the B2D and B2D+BIO

	Service-demand	Efficiency	Renewables	Nuclear	Fossil fuel switching	Fossil fuel CCS	BECCS
B2D	22	1	42	14	3	7	11
B2D+BIO	19	1	47	13	3	5	12

Table 6-18 shows that the additional biomass potential in the B2D+BIO has a large effect of GWP loss recovery. While in the B2D, the cumulative GWP loss is 3.5%, this in the B2D+BIO is less than 3.2%, meaning that each PJ of the additional biomass potential saves around 27.4 thousand dollars of the cumulative GWP, which is noticeably higher than that of the non-biomass renewables (i.e., 2.4 K$/PJ). This confirms the importance of the availability of sustainable biomass in offsetting the negative impacts of the decarbonization policy. Interestingly, the strongest reduction in annual GWP loss occurs around 2060 (when the energy system needs to reach carbon-neutrality).

A look at the regional level reveals that in relative terms, Africa benefits the most from the additional biomass potential. While the cumulative GDP loss in Africa in the B2D is 2.8%, this in the B2D+BIO is 2.3%. This denotes that bioenergy which has a considerable exploitable potential in Africa, is a key measure for this region to move toward the well-below 2°C target. Therefore, it is essential to support the development and implementation of a sustainable bioenergy production in Africa. In addition, a framework of regulations and comprehensive infrastructure are needed to utilize biofuels in different sectors, appropriately.

Table 6-18: Annual GWP losses (%) in the B2D and the B2D+BIO, relative to the Base

	2030	2040	2050	2060	2070	2080	2090	2100	2020-2100
B2D	2.3	3.3	4.0	4.5	4.0	3.7	3.4	3.1	3.5
B2D+BIO	2.0	2.9	3.5	4.0	3.6	3.3	3.1	3.0	3.2

In a nutshell, the considerable increase of biomass use in all sectors in the B2D+BIO compared to the B2D sheds light on the importance of availability of sustainable biomass resources to reach the ambitious well-below 2°C goal. At the same time, it elevates the necessity of improving the efficiency of production and consumption of bioenergy. Finally, since the deployment of BECCS depends on the size of carbon storage resources, extensive analysis of capacity of bankable storage capacity in all world regions is important for a cost-effective transition.

6.3.12 Role of nuclear limitations

In recent years, global nuclear generation continued to increase gradually. In 2014, with an installed capacity of 398 GW, nuclear supplied around 11% of the global electricity demand. This means that next to hydropower, it was the second largest low-carbon measure in the power sector. This denotes that it should be treated on an equal footing with other low- and zero-carbon measures. The share of OECD countries and non-OECD countries in the global nuclear power generation is 78% and 22%, respectively. However, nuclear faces various challenges associated with public concerns, which have led to new policies that reconsider the role of nuclear in some countries. For instance, the German parliament decided to phase-out nuclear power by 2022 (Knopf et al., 2014). To investigate the impacts of the political and technical limitations of the nuclear power on the role that it plays to meet the decarbonization ambition, this section compares the B2D scenario with the B2D+NUC which assumes 25% higher potential for nuclear energy.

It has already been shown that nuclear power is one of the necessary measures to meet the well-below 2°C goal, cost-effectively (Figure 6-13). In the B2D, its generation share rises to 17% in 2100 and installed capacity grows to about 2500 GW in 2100. Of this, 70% is installed in Non-OECD countries, with China alone accounting for 32% of the total global capacity.

In the B2D+NUC, nuclear plays a more significant role in the power sector than in the B2D. The cumulative nuclear power generation over 2020-2100 in the B2D+NUC is 24% higher than in the B2D (Figure 6-38). Besides providing low-carbon electricity, additional nuclear promotes the flexibility of the power system by offsetting the share of variable renewable sources. In the B2D+NUC, the additional nuclear offsets the use of wind and solar PV. It can be seen that the maximum capacity additions are deployed in almost all regions.

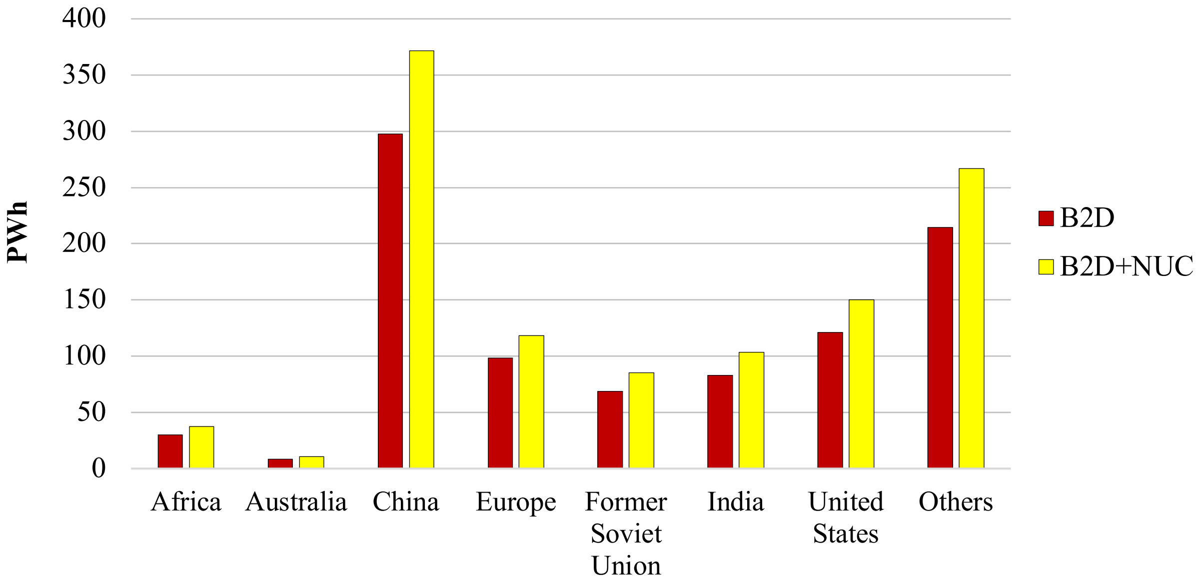


Figure 6-38: Cumulative nuclear power generation over 2020-2100 by region in the B2D and the B2D+NUC

Table 6-19 shows that the contribution of nuclear in the cumulative CO_2 emissions reduction significantly increases from 14% in the B2D to 18% in the B2D+NUC. The higher contribution of nuclear offsets the share of renewables and fossil fuel CCS measures. Moreover, since the additional nuclear slightly reduces prices for meeting the energy-services, the contribution of energy-service demand option decreases from 22% in the B2D to 21% in the B2D+NUC.

Table 6-19: Relative roles of mitigation measures (%) in cumulative CO_2 reduction in the B2D and B2D+NUC

	Service-demand	**Efficiency**	**Renewables**	**Nuclear**	**Fossil fuel switching**	**Fossil fuel CCS**	**BECCS**
B2D	22	1	42	14	3	7	11
B2D+NUC	21	1	40	18	3	6	11

Although nuclear is a very capital-intensive technology, the additional nuclear capacity in the B2D+NUC offsets GWP losses caused by climate policy. In the B2D+NUC, the cumulative GWP loss over the period 2020-2100 is 3.4% which is 0.1% lower than in the B2D (Table 6-20). In other words, each PJ of the additional nuclear potential saves more than 8.5 thousand dollars of the cumulative GWP.

Table 6-20: GWP losses (%) in the B2D and the B2D+NUC, relative to the Base

	2030	2040	2050	2060	2070	2080	2090	2100	2020-2100
B2D	2.3	3.3	4.0	4.5	4.0	3.7	3.4	3.1	3.5
B2D+NUC	2.2	3.3	3.9	4.4	3.9	3.6	3.3	3.0	3.4

6.3.13 Role of energy-service demand reductions

The level of energy-service demand reductions depends on the costs of alternative technologies and fuels available to meet the service demands, costs of the other production input factors (i.e., capital-labor) and the size of the elasticity of substitution. In order to provide more insight into the mitigation role of price-induced energy-service demand reductions, this section compares the B2D scenario with the B2D-DEM that excludes this mitigation measure, and with the B2D-VES which assumes the elasticity of substitution varies as in Figure 6-6.

Excluding energy-service demand reduction option in the B2D-DEM scenario reveals that technological measures are sufficient to stay well-below 2°C. Figure 6-39 shows that in this scenario, deployment of the technological measures, especially renewables (excluding BECCS) is scaled up. This option is by far the largest contributor in the B2D-DEM, providing 59% of the cumulative reduction. Besides the significantly high technical potential for renewables and limited potential of other mitigation measures (e.g. nuclear and CCS), this is because renewables can be directly used by the end-use sectors, providing higher flexibility to the system. In the B2D-DEM, the cumulative direct-use of renewables (excluding biomass) by end-use sectors is more than 32% compared to that in the B2D. Although the importance of BECCS is already recognized, its contribution does not vary among scenarios. This is mainly due to the limited availability of biomass for energy purposes.

On the other hand, it has been recognized that decarbonizing the power sector and allowing electricity to substitute fossil fuels in less flexible end-use sectors (e.g., transport) is a cost-effective strategy for all regions. As discussed in section 6.3.5, in order to shift from the Base to the B2D electricity demand almost doubles in 2100. Such a rapid and strong growth in electricity demand may bring new challenges to the power sector. However, excluding energy-service demand reductions in the B2D-DEM leads to even further increase in electricity demand. Figure 6-40 depicts that in 2100 electricity demand in the B2D-DEM is 37% (40 PWh) higher than in the B2D. It can be concluded that reducing energy-service demands can noticeably offset the additional burden on the power sector and consequently reduce the level of investments in the power sector.

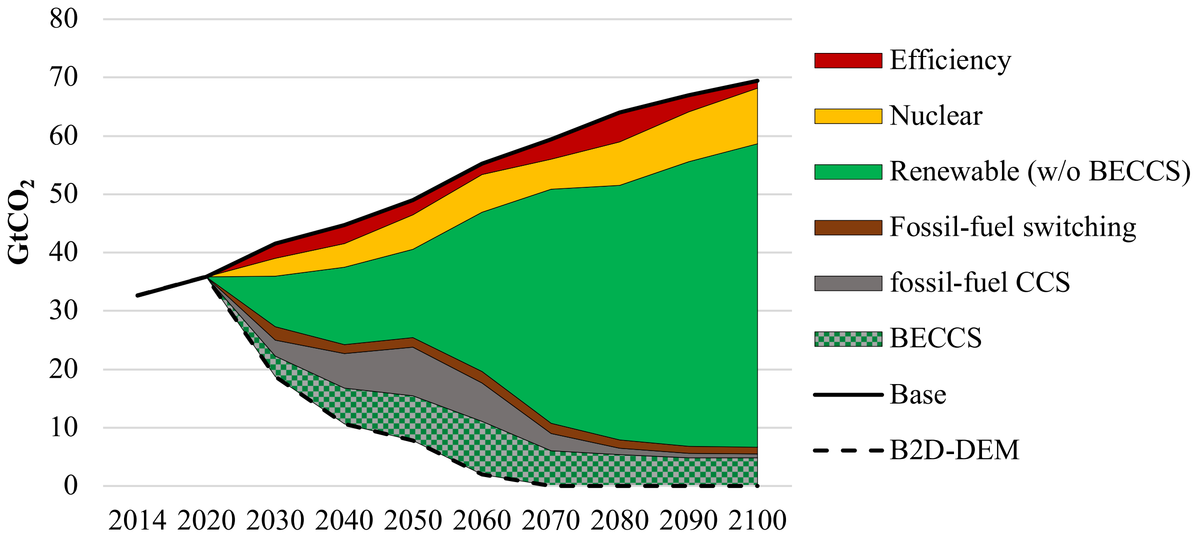


Figure 6-39: Global CO_2 emissions reductions from the Base to the B2D-DEM by mitigation measures

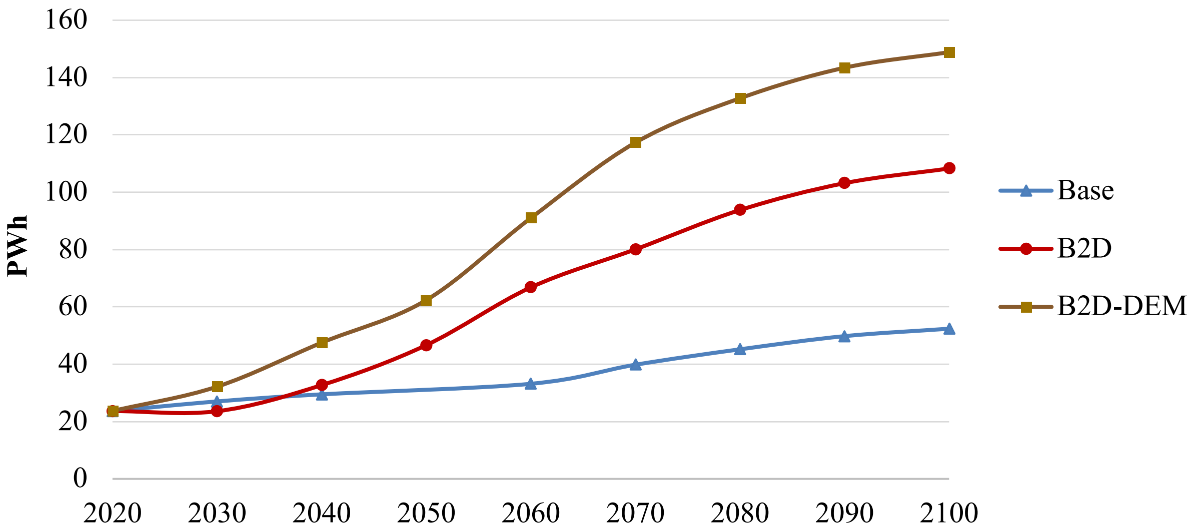


Figure 6-40: Global annual final electricity demand by scenario

Analysis of CO_2 abatement marginal cost indicates that reducing energy-service demands has a significant impact on the direct costs of CO_2 emissions. Figure 6-41 illustrates that compared to the B2D, the annual marginal abatement costs in the B2D-DEM rise more sharply, especially in the second half of the century. In 2100, the marginal abatement cost in the B2D-DEM is almost 7200 \$/tCO_2 which is around three times higher than that in the B2D. It can be concluded that price-induced energy-service demand reductions play a crucial role in ensuring a more cost-effective transition to the well-below 2°C ambition.

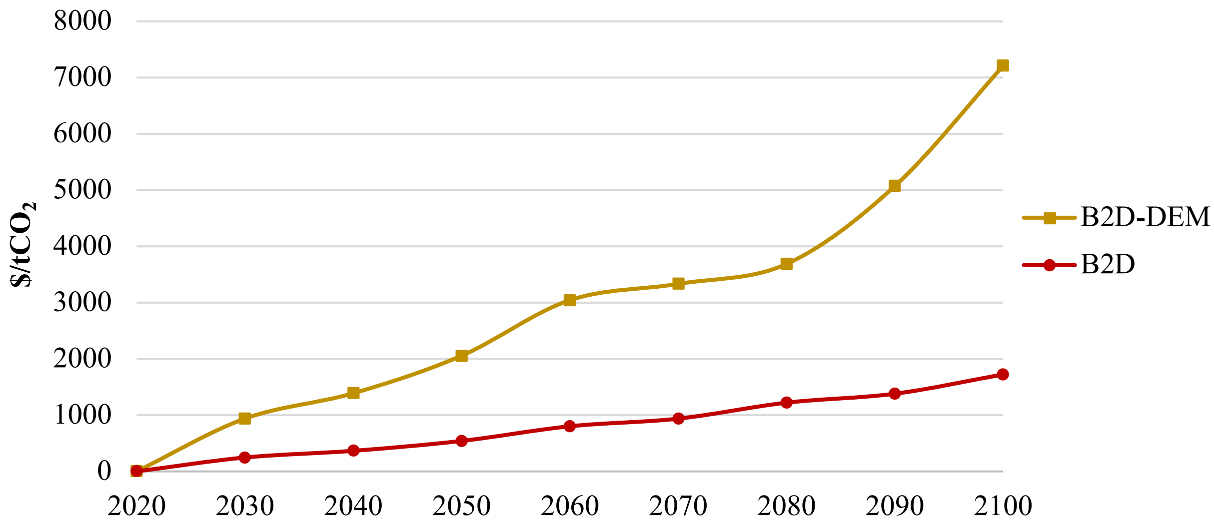


Figure 6-41: Annual CO_2 abatement marginal cost in the B2D and the B2D-DEM

So far, it has been recognized that reducing energy-service demands plays an important role in facilitating a more sustainable and affordable move toward the well-below 2°C. However, to provide a more comprehensive assessment, it is necessary to analyze how region-specific variable elasticity of substitutions may influence the role of energy-service demand reduction in each region. In fact, the level of energy-service demand reductions depends on the costs of alternative technologies and fuels available to meet the energy-service demands, costs of the other production input factors (i.e., capital-labor) and the size of the elasticity of substitution. Figure 6-42 depicts energy-service demand reduction levels for six different regions under the B2D and the B2D-VES scenarios, relative to the Base.

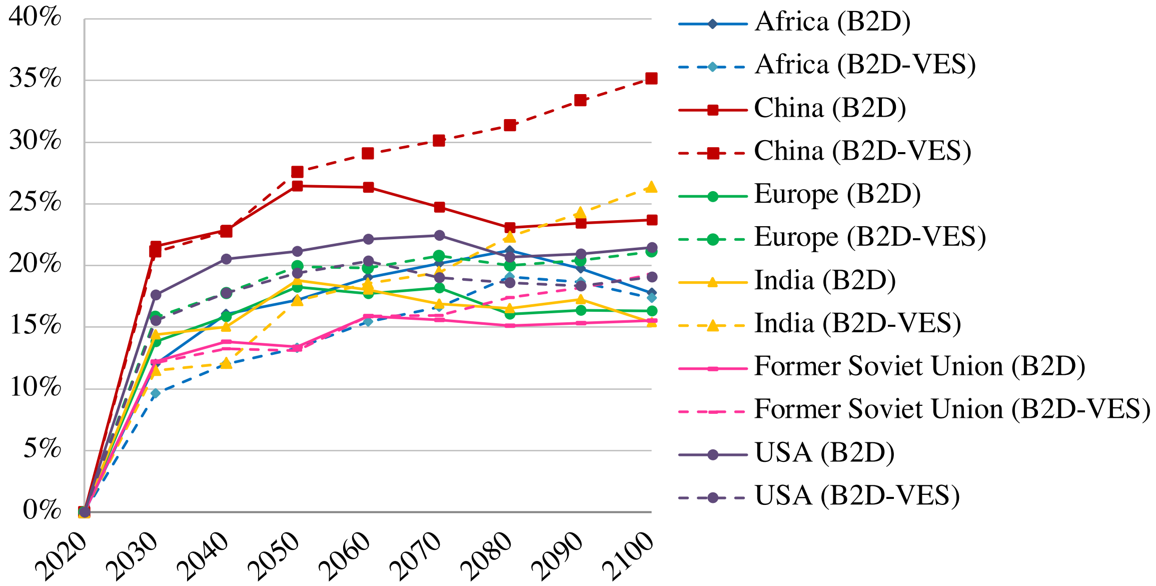


Figure 6-42: Energy-service demand reduction level for six regions under the B2D and B2D-VES scenarios, relative to the Base

The urgency of putting the ambitious well-below 2°C policy into place and limited availability of cost-effective technological options in the near future impose a “price-shock”, leading to significantly higher energy-service prices over the next 10 to 15 years. As a result, energy-service demands in both scenarios experience a notable reduction over the period 2020-2030. In both scenarios, relative energy-service demand reductions increase over time towards the end of the century. In most of the regions, the level of energy-service demand reductions in both scenarios is almost the same in the short to medium term. However, increasing energy-service prices and the higher elasticity of substitutions in the B2D-VES, favors higher reductions in energy-service demands in this scenario in the long-term. This is especially true for developing regions such as China and India, which experience rapid economic growth.

It is noteworthy that although in the B2D-VES scenario India has the highest elasticity of substitution in 2100, China represents the most significant energy-service demand reductions over the whole century. This is also true of the B2D scenario. This issue elevates the importance of the role that energy-service demands in China will play in reaching the mitigation ambition.

A look on the sectoral level is necessary for a more rigorous evaluation of the role of energy-service demand reductions. For this purpose, emissions from secondary energy carriers, such as electricity, are accounted for in each end-use sector. As presented in Figure 6-43, in both scenarios, energy-service demand reductions play the most critical role in decarbonizing the industry, followed by the transport sector. A reasonable explanation for this issue is the limited and relatively expensive abatement opportunities in these two sectors. In fact, the challenges of decoupling expanding demands for the industry and transport sectors from CO_2 emissions will require considerable changes in their current structure and processes, which may dramatically increase the prices of energy services. As a result, price-induced energy-service demand experiences a significant reduction. In contrast, the other sectors provide relatively cheap mitigation measures as their decarbonization are mainly characterized by electrification and decarbonization of the electricity sector.

From Table 6-21 it can be observed that the share of energy-service demand reductions in the cumulative CO_2 emissions reduction increases from 22% in the B2D to 25% in the B2D-VES. As discussed, the increased contribution of this measure is mainly balanced by the lower share of renewables.

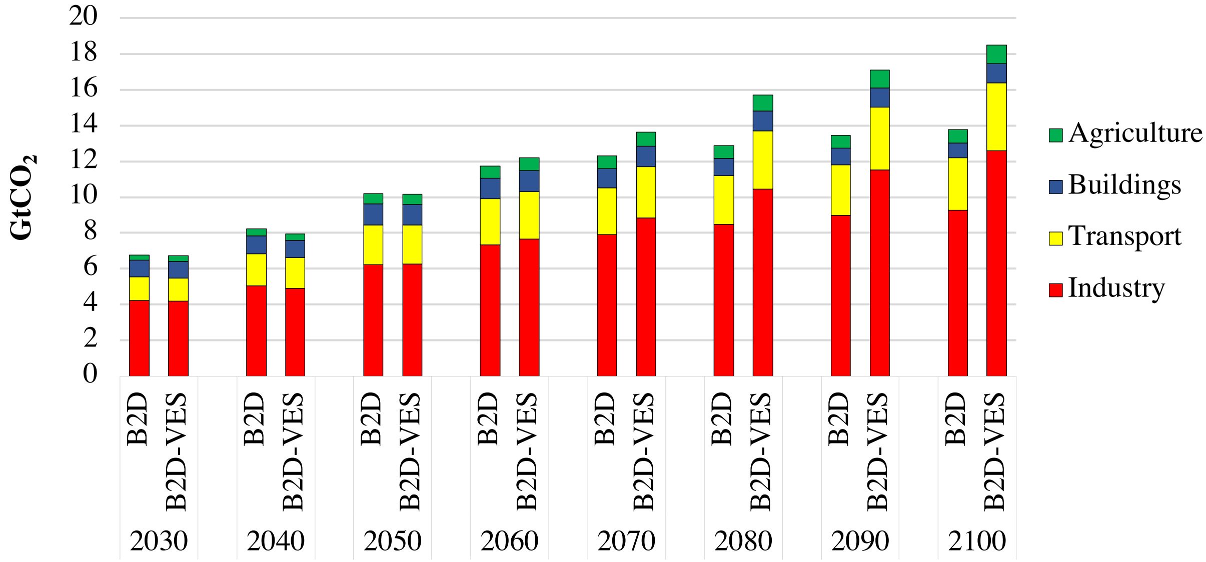


Figure 6-43: Contribution of energy-service demand reduction to the global overall CO_2 emissions reduction

Table 6-21: Relative roles of mitigation measures (%) in cumulative CO_2 reduction in the B2D and B2D-VES

	Service-demand	**Efficiency**	**Renewables**	**Nuclear**	**Fossil fuel switching**	**Fossil fuel CCS**	**BECCS**
B2D	22	1	42	14	3	7	11
B2D-VES	25	1	39	14	3	7	11

For a more comprehensive assessment of the mitigation role of energy-service demand reductions it is necessary to analyze macroeconomic implications of the relevant scenarios. In this regard, Figure 6-44 depicts regional GDP losses in the B2D and B2D-VES scenarios. It can be observed that if economies become more flexible to replace energy-service demands with other production inputs, they will be less affected by ambitious global mitigation targets. Therefore, energy-service demand reductions help to recover some of the losses in GDP caused by the climate policy. This implies that besides decarbonization of the energy mix, achieving the well-below 2°C target requires a considerable decoupling between economic growth and energy consumption. In relative terms, China benefits the most from the higher elasticity of substitution in 2100 as its GDP in the B2D-VES is 0.9% (1024 M$) higher than in the B2D.

On the other hand, the figure shows a sharp reduction in regional GDP in the period immediately after policy is tightened i.e. between 2020 and 2030 for both scenarios. However, in developing regions (e.g., Africa and India) where the elasticity of substitution in the B2D-VES is lower than the B2D in 2030, the differences between GDP losses in these scenarios are more significant. This once more shows that energy-service demand reductions play an especially important role in the short-term when there are limited technological measures available.

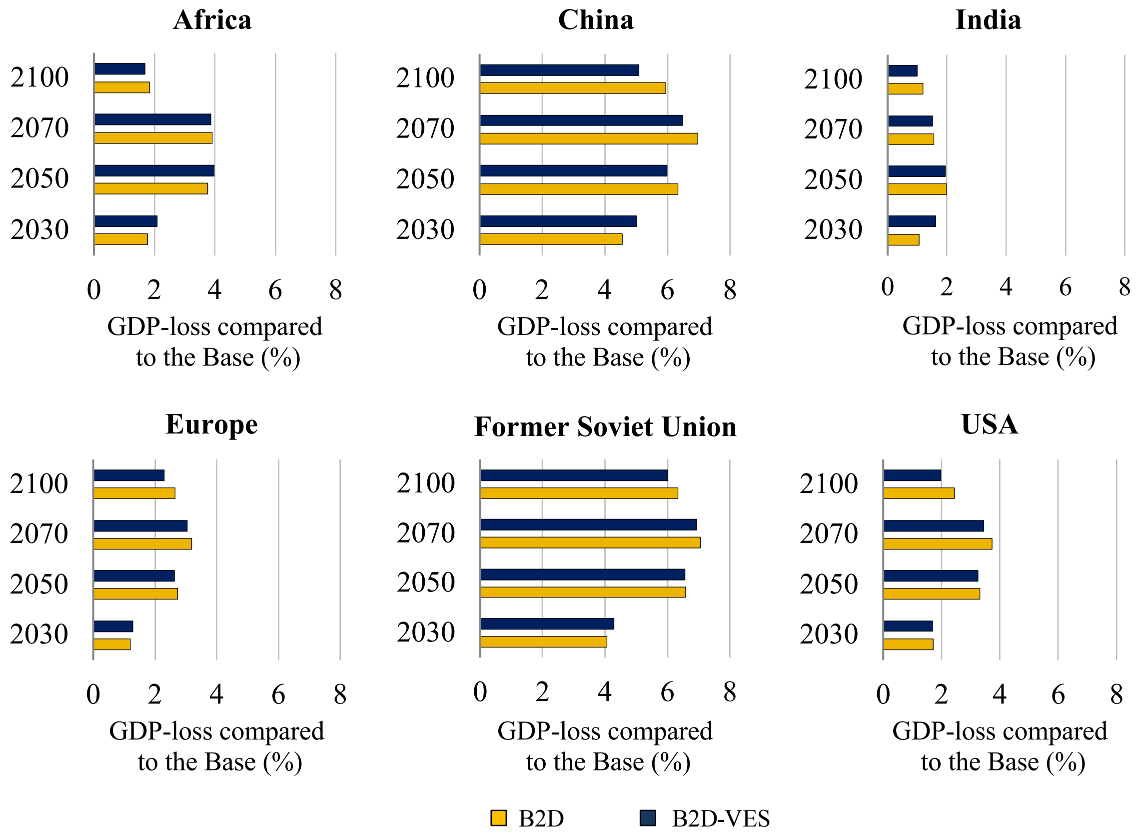


Figure 6-44: GDP-Losses (%) compare to the Base by region and scenario

7 Summary and outlook

7.1 Summary

This dissertation is an investigation of the required energy system transformations and the associated price-dependent energy-service demand reductions in order to hold the increase in global average temperature well-below 2°C above pre-industrial levels. The analysis was carried out using the hybrid TIAM-MACRO model which is a combination of a bottom-up, technology-rich model, TIAM (TIMES Integrated Assessment Model) and a top-down, macroeconomic model, MACRO. In the original TIAM-MACRO model, the elasticity of substitution which denotes the ease or difficulty of substituting energy-service demands with the other production factors in the model (i.e., capital-labor), holds a constant value for all regions over the long-term time horizon. To provide more insight, it was assumed that the elasticity parameter can vary across regions and over time. To implement this feature, the production function of the MACRO model was normalized. The normalization provided other benefits such as addressing the issue of dimensionality. In fact, the original production function of the MACRO model contains dimensional constants which are economically meaningless.

Considering the uncertainties in technical potentials and limitations of technological measures, a set of scenarios with different assumptions concerning the maximum technical/realizable potentials was considered. Furthermore, for a deeper analysis of the role of price-induced energy-service demand reductions, additional scenarios containing different assumptions regarding this measure have been included. The following section presents key messages concluded from the scenario analysis of this study.

- Our current understanding of mitigation measures and the pace and scale of efforts needed to achieve carbon neutrality in the global energy system by around 2065 and in the global power sector before 2040 show that the window for achieving the well-below 2°C target (without overshooting) is rapidly closing. This confirms that there would be almost no room for delay and elevates the importance of early action in meeting such an ambitious target, which avoids lock-in of current carbon intensive technologies and infrastructure.
- The well-below 2°C target requires the power sector to achieve net-zero emissions before 2040 and becomes a negative source of emissions in the post 2040 period, while electricity demand almost doubles by 2100. This implies that decarbonizing electricity generation and substituting fossil fuels with the decarbonized electricity in less-flexible end-use sectors (e.g. mobility) is a cost-effective mitigation strategy. However, electricity generation does not necessarily need to be deeply decarbonized to benefit reducing emissions. In essence, since efficiency of electric end-use technologies is usually higher than their fossil fuel alternatives, electrification of end-use services can itself lead to lower CO_2 emissions. This shows the importance of electrification of end uses in this context. However, a rapid

and strong growth in electricity demand may bring new challenges to the power sector. In this regard, reducing energy-service demands plays a critical role in offsetting the additional pressure on the power sector.

- Significant transformations in the transport sector are required to meet the ambitious well-below 2°C target. It was identified that this sector benefits mainly from electrification to decarbonize. Virtually, all passenger and light-commercial vehicles will be electric by the end of the century. However, while electrification is best placed to replace fossil fuel alternatives mainly in short-distance transport modes and public transport, advanced low-carbon fuels are necessary for other modes which are more difficult to electrify. In this regard, hydrogen is considered as a suitable mitigation measure. In addition, the possibility of producing hydrogen from biomass in combination with CCS can provide higher benefits for the energy sector. In the main well-below 2°C scenario (B2D), hydrogen provides around 10% of the global transport final energy use in 2100. Therefore, stable and long-term policy frameworks are essential to facilitate expansion of the hydrogen industry and enable the related capital and production cost reductions. Moreover, advanced biofuels could also have a relevant role in the future transport sector (especially for shipping and aviation modes). For aviation, sustainable biofuels supply chain development and appropriate strategies to reduce related costs are essential. Finally, reducing price-dependent energy-service demands was found to be an essential measure in reducing CO_2 emissions from the transport sector. It accounts for more than 37% of the cumulative CO_2 emissions reduction in this sector from the Base to B2D.
- To achieve the well-below 2°C cost-effectively, it is necessary to avoid lock-in of current emissions-intensive technologies and infrastructures in the industry sector. Besides continued enhancement of energy efficiency, this implies major structural changes to employ the essential mitigation measures, such as electrification and use of hydrogen. Such changes require notable investment in technology innovation across a portfolio of technologies and subsectors, which may lead to considerably higher prices for final products. As a result, to ensure the cost-effectiveness of the transition, this sector will experience a notable reduction in the energy-services, especially in the short-term. The necessity of reducing energy-services implicitly conveys a message that the strategies that aim at offsetting production of materials, such as increasing scrap recycling rates, would be of crucial importance in this context.
- Meeting the well-below 2°C target implies that buildings (the residential and commercial sectors) and the agriculture sector need to move toward carbon-neutrality by the end of the century. Despite this, due to the limited availability of sustainable bioenergy resources and the urgency of biomass use in decarbonizing sectors like electricity and transport, biomass consumption in these sectors falls notably over the century. This is especially important for developing countries where over 2.5 billion people rely on biomass to meet

their cooking and heating energy. To reduce pressure on biomass, other renewables and electricity increase their contribution substantially. However, since customers generally prefer cost-effective solutions due to their financial concerns, replacing fossil fuel based technologies with low-carbon alternatives might be challenging.

- Renewables will feature increasingly as an essential element in decarbonizing energy sectors of all nations. It was found that renewables (excluding BECCS) dominate other measures, accounting for about 42% of the cumulative CO_2 emissions reduction from the Base to B2D. Therefore, it is important to rapidly address both economic and non-economic challenges of renewables. On the other hand, the accelerated deployment of variable renewable sources needs high system flexibility to avoid integration challenges. While contributions over the long-term of solar and wind are not significantly impacted by the additional technical potential, hydro is heavily impacted.
- Nuclear is a mature mitigation measure. In the B2D, nuclear ramps up its contribution toward the end of the century, representing 14% of the cumulative CO_2 emissions reduction. However, it faces various challenges: not only public concerns about radioactive waste production and accidental radiation release risks, but also economic challenges, since it is a very capital-intensive technology. Despite challenges, nuclear is considered as a promising non-emitting base-load power source. However, its contribution in meeting an ambition mitigation target heavily depends on its potential. In a well-below 2°C pathway, nuclear growth remains strongest in Asia, especially China.
- A deep emissions reduction requires notable deployment of CCS technologies in electricity, industry and other transformation sectors in the coming decades. According to the main findings, moving toward the well-below 2°C necessitates the deployment of both fossil fuel and biomass CCS technologies, especially in the first half of the century. It was shown that in almost all regions the effectiveness of CCS relies on the capacity of CO_2 storages. Hence, coordinated and extensive assessment of global CO_2 storage potential is required to prove secure, sustainable and practical CO_2 storage areas.
- It was also shown that it is possible to reach the well-below 2°C target without overshooting the carbon budget. This, however, does not negate the importance of BECCS, which produces negative-emissions, in the transition. In fact, BECCS is needed to compensate for residual emissions in sectors where direct mitigation is more challenging, for instance in shipping and some industrial processes. In the B2D, it delivers 16% of the cumulative negative emissions in the period to 2100. Despite the advances made in CCS technology in recent years, no large BECCS power plant operates at a commercial scale. In addition, the availability of bankable carbon storage is recognized as an important factor influencing the deployment of BECCS. However, ahead of any of the concerns related to large-scale deployment of BECCS, the availability of sustainable and sufficiently large biomass supply over the world regions is critical. Therefore, an effective system should address the

risks associated with bioenergy availability to support efficient production and consumption of biomass.

- It was presented that uncertainty concerning the size and function of the elasticity of substitution can have some impacts on mitigation pathways and the associated costs. Nevertheless, this uncertainty does not weaken the key insight that reducing energy-service demands plays an important role in facilitating the transition towards the well-below 2°C target. Furthermore, this measure ensures a more cost-effective transition to the well below 2°C target. Excluding energy-service demand reductions measure significantly increased the marginal abatement costs of meeting the well-below 2°C target.
- Despite the optimized deployment of supply-side and demand-side measures, reaching the well-below 2°C goal comes with considerable negative macroeconomic impacts. Immediately after the decarbonization policy is tightened, the extensive uptake of mitigation measures implies high additional macroeconomic costs. In B2D, the loss in the cumulative GWP over 2020-2100 is 3.5%. At the regional level, GDP losses are more pronounced for fossil fuel producing regions whose economies will rely heavily on fossil fuels. In relative terms, China and Former Soviet Union suffer the most in their cumulative GDP over 2020-2100, respectively.
- It was also observed that if economies become more flexible to replace energy-service demands with other production inputs, they will be less affected by the ambitious global mitigation target. This implies that besides decarbonization of the energy mix, achieving the well-below 2°C target requires a considerable decoupling between energy demand and economic growth. In relative terms, China benefits the most from the higher elasticity of substitution in the 2100 as it GDP in the well-below 2°C scenario (B2D-VES) with variable elasticity of substitution (B2D-VES) is more than 1000 M$ higher than in the B2D.

7.2 Outlook

TIAM is a technology-rich energy system model. Although it covers the industry sector in a detailed manner, given the importance of the cement industry as one of the most energy-intensive and carbon-intensive industries, future work can involve further disaggregation of the industry sector to represent the cement industry as a separate sub-sector. Furthermore, in order to provide additional insights concerning the role of price-dependent energy-service demand changes in the transport sector, further consideration can be given to modeling modal shift, which enables reductions in demand of a transport mode through shifting to a different mode. However, efforts of raising the level of detail in a global energy system model are often restricted by the limited availability of reliable data, especially in developing countries such as China. In this regard, the research on the empirical data foundation of energy systems and the integration of more reliable data sources into the energy system model should be strengthened.

Moreover, TIAM uses exogenous assumptions on technological development to represent technology improvements. Typically, it is considered that while notable cost reductions are possible as a result of R&D before a technology enters markets, there is a possibility for further cost reductions as a result of learning by-doing, economies of scale and continued R&D. Although, technological development in TIAM are drawn on the basis of learning curve studies that assume a particular level of deployment of technologies, introducing endogenous technology learning can provide more insight into the future evolution of the energy system. This means that cost reductions of a certain technology are modeled as a function of the cumulative installed capacity. Hence, future research might implement technology learning endogenously in the TIAM model.

Costs considered in this dissertation (e.g., GDP losses) refer to gross costs of reaching a mitigation target, compared to a baseline case which is not influenced by climate change. Hence, it did not take into account costs of adapting to climate change, nor effects of damages provoked by global warming. However, potential damage and adaptation costs could be considerable in many countries. Therefore, despite the large uncertainties in the assessment of these costs, further research is needed to include damage costs and adaptation actions in such an analysis.

The decision to implement energy-service demands reduction measure is dependent not only on the benefits (e.g. recovering macroeconomic impacts), but also the costs and barriers of the measure. Hence, for a more realistic assessment of the future contribution of energy-service demands reduction, one can take the associated costs and barriers into account. On the other hand, considering lack of empirical studies focusing on variable elasticity of substitution production functions with energy, capital and labor inputs, analyzing different functional forms (endogenous and exogenous) for elasticity of substitution can provide more insights into the role of this measure in tackling long-term decarbonization targets.

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Appendix

A.1 A review of the applications of the TIAM model

As discussed, TIAM benefits from a high level of detail in its description of the energy system and covers a relatively high number of regions. Moreover, it encompasses three main GHG emissions and includes a climate module. Furthermore, it allows stochastic modeling. Table A-1 compares TIAM with other global energy system models.

Due to its advantages, the model, has been applied in several peer-reviewed journal articles. Although TIAM is a global model, its applications are not restricted to the global scale. That is to say, due to the detailed representation of the regional energy systems, a number of studies have been carried out at the regional scale. While Table A-2 provides the applications of the TIAM model at the national and regional scales, Table A-3 presents the applications at the global scale. It is important to be mentioned that the presented review does not distinguish between the standard TIAM model and other versions (e.g., TIAM-UCL, TIAM-FR and TIAM-ECN)[21]. These tables clearly show that the model is a suitable tool especially in the context of climate change mitigation.

Table A-1: TIAM in comparison with other global energy system models – Based on Føyn et al. (2011)

Model name	**Level of detail**	**Number of regions**	**System description Gases**	**Climate module**	**Endogenous technology learning**	**Possibility of stochastic modeling**
TIAM	High	15	CO_2, CH_4, N_2O	Yes	No	Yes
POLES	Medium	18	CO_2	No	Yes	No
IEA WEM	High	21	CO_2	No	No	No
AIM	Hugh	9	CO_2, CH_4, N_2O	Yes	No	No
ASF	Medium	9	CO_2, CH_4, N_2O	Yes	No	No
IMAGE	Medium	13	All Kyoto gases	Yes	Yes	Yes
MESSAGE-Global	High	10	All Kyoto gases	Yes	Yes	Yes
MiniCAM	Low	9	All Kyoto gases	Yes	No	No

[21] These versions are mainly different in terms of the number of regions.

Table A-2: Existing applications of the TIAM model at national and regional scales

Study	Regional focus	Sectoral focus	Research focus
Syri et al. (2008)	Europe	All	Pathways to meet 2°C target
Koljonen and Lehtilä (2012)	Asia	All	The Impact of energy demand uncertainties on climate change mitigation
Van der Zwaan et al. (2013)	Europe	Transport	Pathways toward less carbon transport sector as well as the world under a climate target
Van der Zwaan et al. (2013a)	Middle-East	All	Potential for renewable energy jobs
Gambhir et al. (2014)	India	All	Pathways toward a low-carbon economy
Anandarajah and Gambhir (2014)	India	All	Role of renewables in tackling climate change mitigation target
Di et al. (2015)	Argentina	All	Emission reduction pathways in Argentina
Calvin et al. (2015)	Latin America	All	pathway of agriculture, forestry and other land use GHG emissions in Latin America
Dai and Mischke, (2014)	China	All	Decarbonization pathways in China
Dai et al. (2015)	China	All	Projection of China energy use and emissions
Kober et al. (2016)	Latin America	All	Analysis of carbon pricing on energy consumption and GDP
Gerboni and Grosso (2016)	Europe	All	Investigation of future hydrogen penetration at local scale
Lima et al. (2016)	Brazil	All	Analysis of the effects of market-based mechanisms and carbon emission restrictions on the energy system
Calderon et al. (2016)	Colombia	All	Investigation of the effects of implementing carbon taxes and abatement targets on the energy system
Di Sbroiavacca et al. (2016)	Argentina	All	Evaluation of the impact of a variety of climate change control policies including carbon pricing and emission constraints

Table A-3: Existing applications of the TIAM model at the global scale

Study	Sectoral focus	Research focus
Koljonen et al. (2009)	All	Role of CCS and renewables in tackling climate change
Føyn et al. (2011)	All	Pathways to 100% renewable-based global energy system
Anandarajah et al. (2013)	Transport	Role of hydrogen and electricity in decarbonizing transport sector
Ricci and Selosse (2013)	All	Potential role of Biomass with CCS technologies in meeting CO_2 mitigation targets.
Gracceva and Zeniewski (2013)	All	Uncertainties associated with production cost and size of shale gas resources
Selosse et al. (2013)	Electricity	Influences of reduction of nuclear power on the electricity sector with and without CCS
Gracceva and Zeniewski (2014)	All	Interactions between energy security and climate change
Rösler et al. (2014)	Transport	Impacts of climate mitigation policies and high oil prices on passenger cars
Selosse and Ricci (2014)	All	Possible deployment of global Biomass with CCS to achieve climate targets
García-Gusano et al. (2016)	All	Role discount rates in energy system models
Kesicki and Anandarajah (2011)	All	Role of energy-service demand reduction in global climate change mitigation
Labriet et al. (2012)	All	Climate and technological uncertainties on the evolution of the world energy system
Bouckaert et al. (2014)	Electricity	Impact of water scarcity on the global electricity generation
McGlade and Ekins (2014)	All	Volume of oil that can be used under CO_2 reduction scenarios
Morfeldt et al. (2014)	Industry	Impacts of climate policies on steel production technologies and scrap use
Price and Keppo (2016)	All	Maximally different global energy system transition pathways
Edelenbosch et al., (2017)	Industry	Projection of baseline and mitigation scenarios for the global overall industry sector

A.3 Number of end-use technologies and the associated input fuels in the TIAM model

This section presents the number of end-use technologies and the associated input fuels of energy-services in the TIAM model. However, since the industry sector encompasses a chain of processes to fulfill the energy-services, the following tables only present information on residential, commercial and transport sectors.

Table A-4: Number of end-use technologies and the associated input fuels of energy-services in the residential sector

Energy-services	**Number of end-use technologies**	**Input fuel(s)**			
		Fossil fuels	***Renewables***	***Electricity***	***Heat***
Space heating	24	■	■	■	■
Space cooling	12	■	■	■	
Water heating	20	■	■	■	■
Lighting	8	■		■	
Cooking	9	■	■	■	
Refrigeration	4			■	
Clothes washing	3			■	
Clothes drying	4	■		■	
Dish washing	4			■	
Electric appliances	2			■	
Other energy uses	11	■	■		

Table A-5: Number of end-use technologies and the associated input fuels of energy-services in the transport sector

Energy-services	**Number of end-use technologies**	**Input fuel(s)**			
		Fossil fuels	***Biofuels***	***Electricity***	***Others****
Auto	18				
Bus	11				
Light truck	18				
Commercial truck	13				
Medium truck	11				
Heavy truck	11				
Two-wheeler	3				
Three-wheeler	3				
International aviation	3				
Domestic aviation	3				
Rail-freight	3				
Rail-passenger	3				
International navigation	3				
Domestic navigation	3				

* Includes hydrogen and methane

Table A-6: Number of end-use technologies and the associated input fuels of energy-services in the commercial sector

Energy-services	**Number of end-use technologies**	**Input fuel(s)**			
		Fossil fuels	***Renewables***	***Electricity***	***Heat***
Space heating	24	■	■	■	■
Space cooling	18	■	■	■	
Water heating	17	■	■	■	■
Lighting	9	■		■	
Cooking	8	■	■	■	
Refrigeration	2			■	
Electric equipment	2			■	
Other energy uses	2	■		■	

A.3 Implementation of the TIAM-MACRO model

The goal of linking TIAM with MACRO is to consider the interconnections between the energy sector and the rest of the economy. The first step in using TIAM-MACRO is to calibrate the model for the baseline scenario (that excludes the policy scenario). The purpose of the calibration procedure is to update the labor growth rates between successive iterations in such a way that they match the user-specified GDP growth rates. Moreover, it calculates the demand decoupling factors such that the projected energy-service demands match the energy-service demand variables in the TMSA model. Figure A-1 shows the flow diagram of the calibration routine.

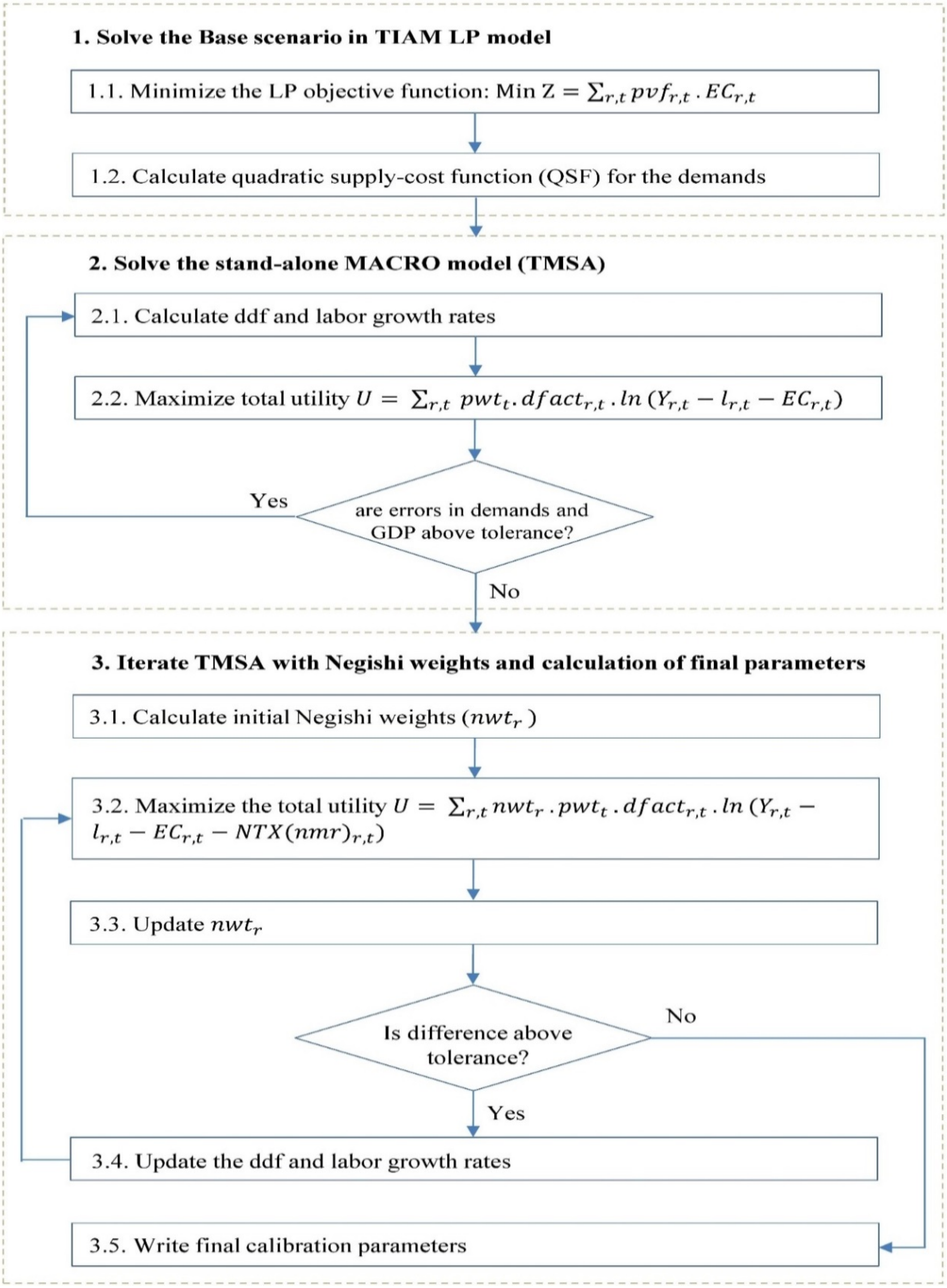

Figure A-1: Algorithm for the baseline calibration – Based on Kypreos and Lehtila (2015)

The second step runs the policy scenario. It includes the calibration values calculated by the previous step. It iterates between TIAM and TMSA on the Negishi weights and energy-service demand levels in all periods and all regions, until they converge. Figure A-2 shows the decomposition algorithm employed in the model for the policy scenario run.

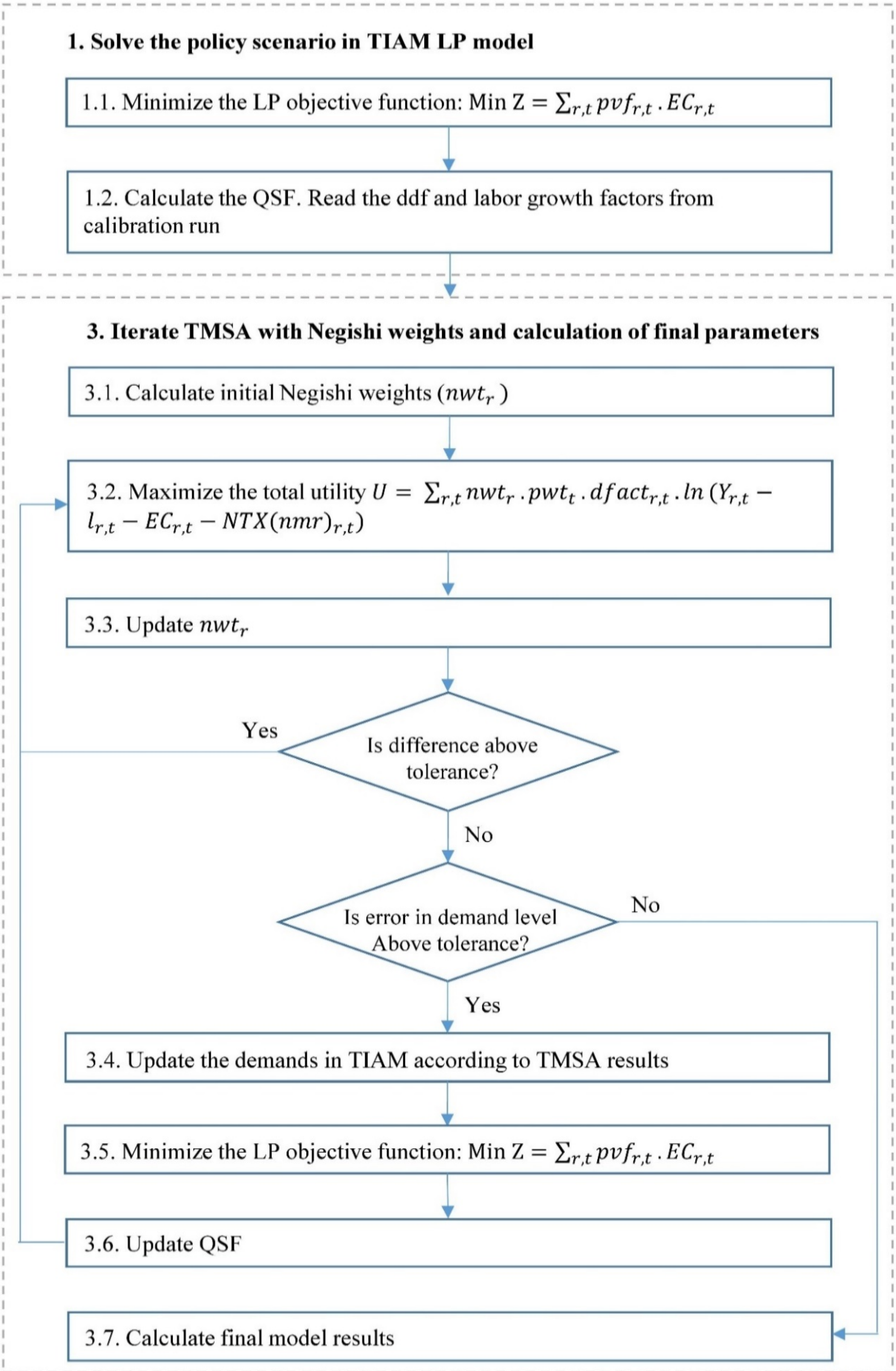

Figure A-2: Algorithm for the policy scenario run – Based on Kypreos and Lehtila (2015)

A.4 Additional scenario assumptions

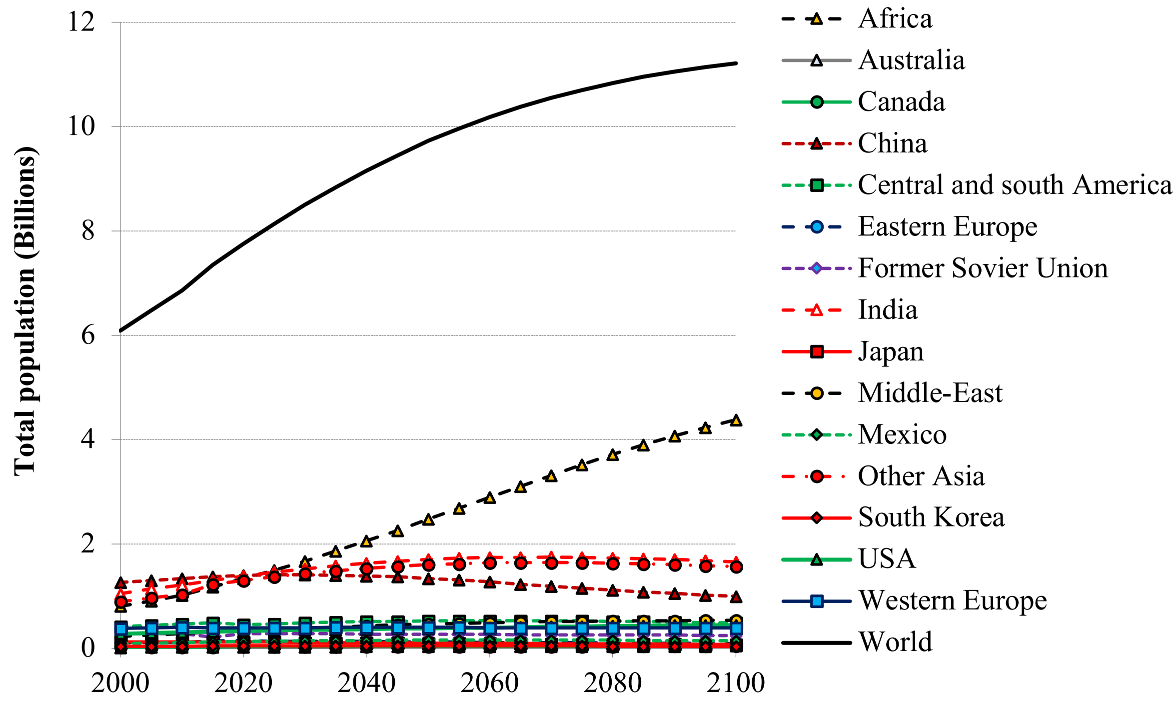

Figure A-3: The global and regional population projections

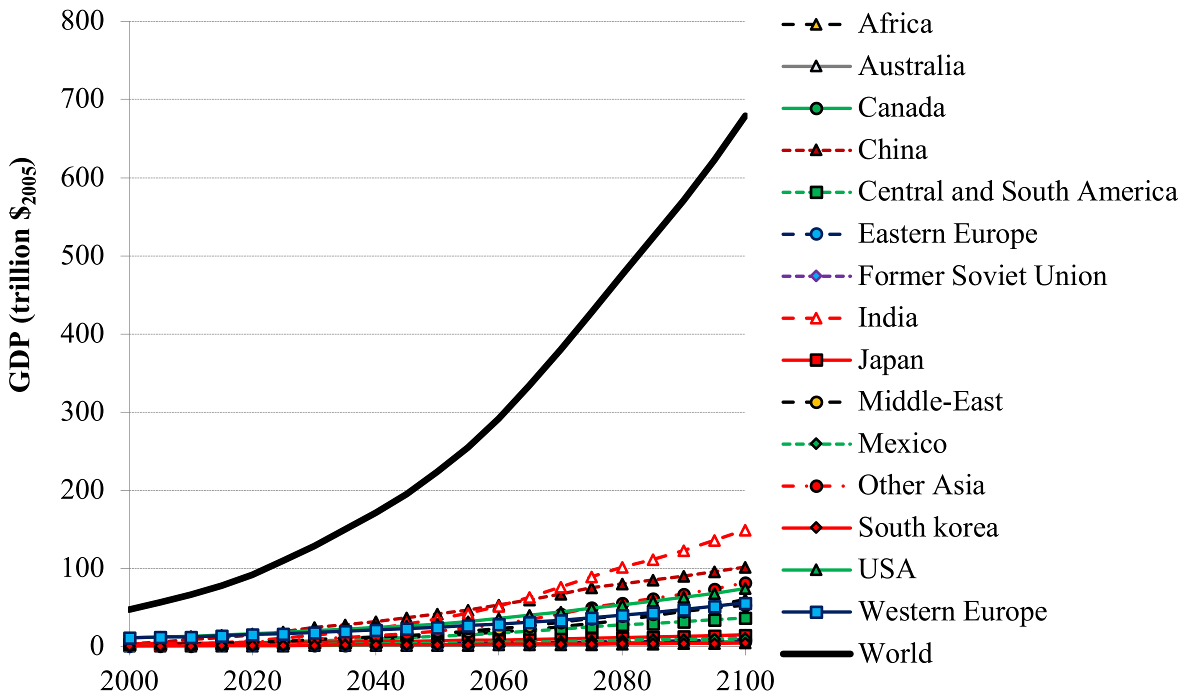

Figure A-4: The global and regional GDP projections

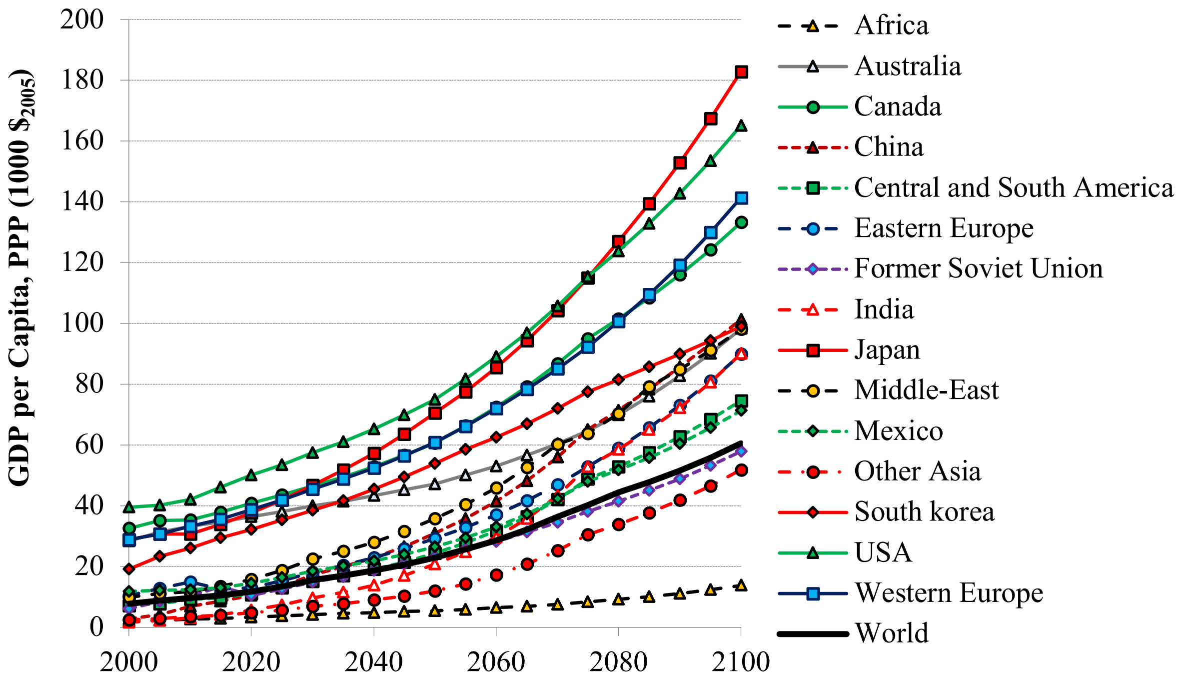

Figure A-5: The global and regional GDP per capita projections

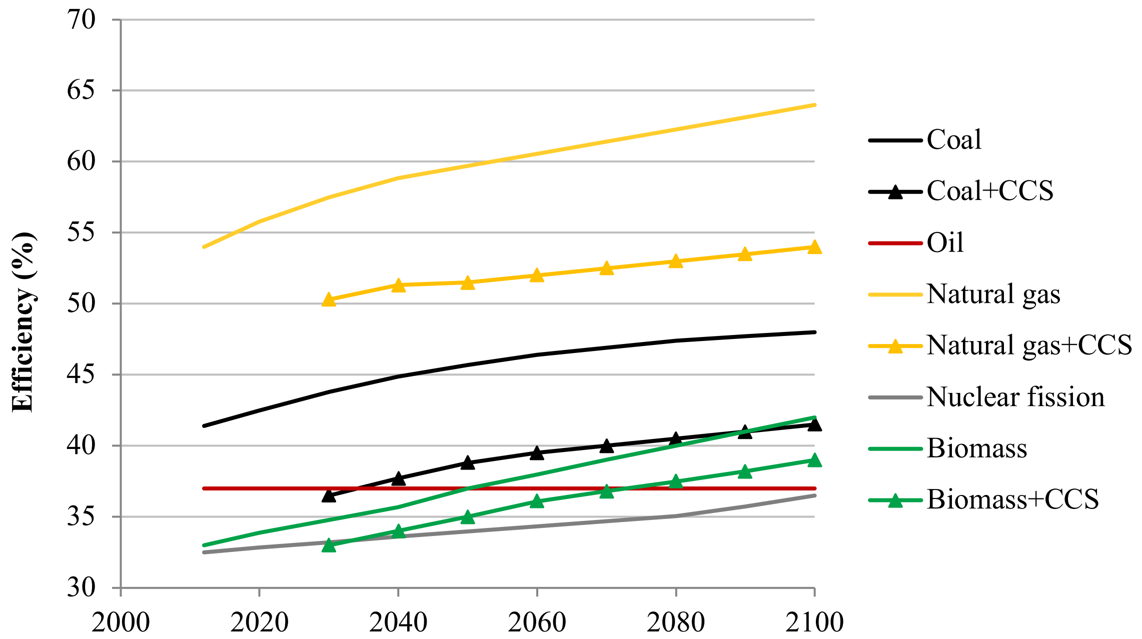

Figure A-6: The efficiency projections for representative electricity generating technologies

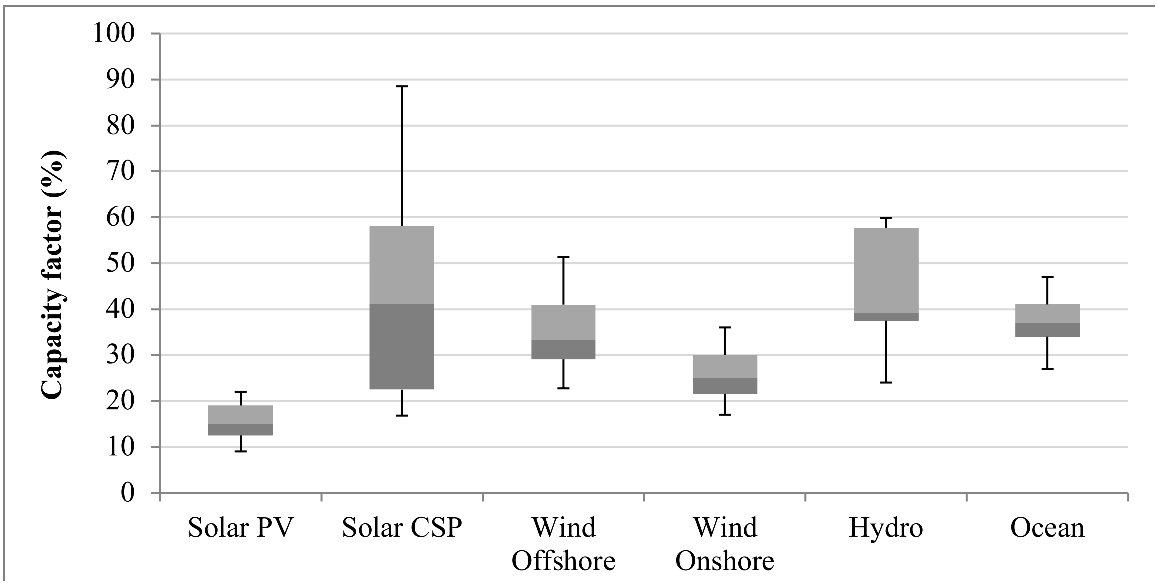

Figure A-7: Box and Whisker plot for capacity factor of electricity generating technologies in the TIAM model (across regions)

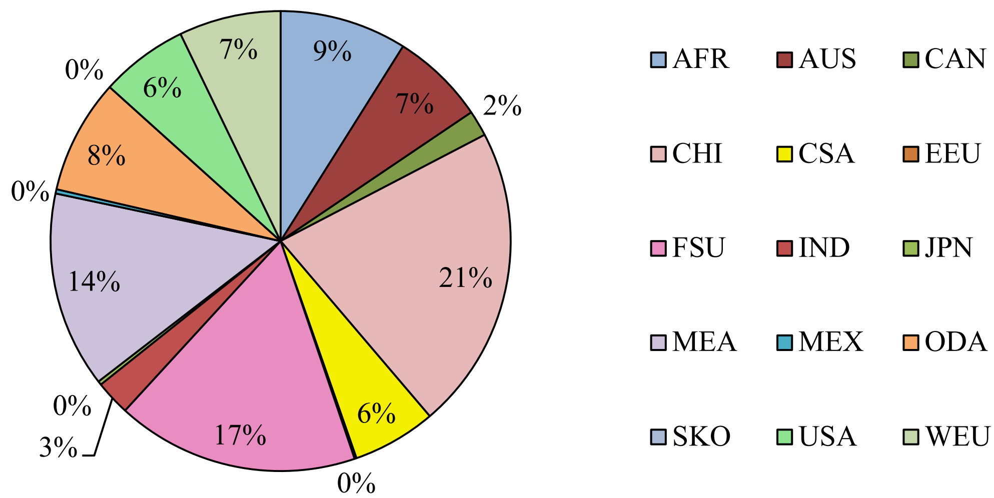

Figure A-8: The regional distribution of the total potential for offshore CO_2 storages

Table A-7: Additional cost components of solar PV, wind onshore and wind offshore

Additional Cost components	**Solar PV**	**Wind onshore**	**Wind offshore**
Information and communication technologies costs	50 $/KW	50 $/KW	50 $/KW
Transmission grid cost	-	300 $/KW	300 $/KW
Distribution grid costs	200 $/KW	200 $/KW	200 $/KW
Offshore connection	-	-	1100 $/KW
Total	**250 $/KW**	**550 $/KW**	**1650 $/KW**

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Content

Climate change is one of the most critical issues facing the world today. In 2015, the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) codified an ambitious long-term global target: holding the increase in the global average temperature well-below 2°C. It is recognized that this goal is a safe guardrail and will reduce negative impacts of climate change, significantly. To meet the target, the energy sector offers a wide range of technological options, namely, energy efficiency improvement, shifting from high carbon-intensive fossil fuels to less carbon-intensive alternatives (e.g. switching from coal to natural gas), and the enhanced use of renewables, nuclear, and Carbon Capture and Storage (CCS). On the other hand, additional investments in cleaner technologies will, ceteris paribus, result in a higher price of energy services and consequently reduce demand for energy-services which is considered as a mitigation measure.

This dissertation aims at exploring, in a systematic manner, the required energy system transformations and the associated price-dependent energy-service demand reductions in order to hold the increase in global average temperature well-below 2°C above pre-industrial levels by 2100. For a more comprehensive assessment, it also evaluates the macroeconomic implications of the climate mitigation policy. The analysis is carried out using a hybrid model which is a combination of a bottom-up, technology-rich model, TIAM (TIMES Integrated Assessment Model) and a top-down, macroeconomic model, MACRO. One of the key parameters of this hybrid model is elasticity of substitution denoting the ease of substituting energy-service demand with other production factors in the model (i.e. capital-labor) as their relative prices change. To provide more insight into the role of energy-service demand reductions, it is additionally assumed that the elasticity parameter varies across regions and over time. Furthermore, due to the uncertainties around the potential for mitigation technologies, a set of different scenarios with respect to the potentials are considered.

The main findings of this study highlight the importance of early action in all energy sectors. Renewables are found to be the main mitigation measure. Furthermore, biomass with CCS is an essential option to compensate for residual emissions in sectors (e.g., transport) where direct mitigation is more challenging. It is also revealed that reaching such an ambitious mitigation target comes with considerable negative macroeconomic impacts, while energy-service demand reductions play an important role in offsetting the impacts.

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