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# Energy transition and carbon inequality : prospective analysis of technology roadmaps for China, France and the United States of America

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Par

**Mme Wenhui TIAN**

Transition Énergétique et Inégalité de Carbone : Une Analyse Prospective des  
Feuilles de Route Technologiques pour la Chine, la France et les États-Unis  
d'Amérique

Energy Transition and Carbon Inequality: Prospective Analysis of Technology  
Roadmaps for China, France and the United States of America

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2015 :**

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The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities.

*Article 3, United Nations Framework Convention on Climate Change, 1992*

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# Acronyms

<b>2DS</b>	2°C Scenario
<b>3Es</b>	Economy, Energy, Environment model
<b>4DS</b>	4°C Scenario
<b>6DS</b>	6°C Scenario
<b>AEO</b>	Annual Energy outlook
<b>AIM</b>	Asian-Pacific Integrated Model
<b>AME</b>	Asian Modeling Exercise
<b>ANCRE</b>	L'Alliance Nationale de Coordination de la Recherche pour l'Energie
<b>APEC</b>	Asian-Pacific Economic Cooperation
<b>AR5</b>	Fifth Assessment Report
<b>BaU</b>	Business-as-Usual
<b>CCS</b>	Carbon Capture and Storage
<b>CGE</b>	Computable General Equilibrium
<b>CN</b>	China
<b>COP</b>	Conference of Parties
<b>CV</b>	Coefficient of Variation
<b>DNE21</b>	Dynamic New Earth 21
<b>E3ME</b>	Energy-Environment-Economy Model for Europe
<b>EFOM</b>	Energy Flow Optimization Model-ENVironment
<b>EIA</b>	U.S. Energy Information Administration
<b>ELC</b>	Enhanced Low Carbon
<b>EPPA</b>	Emissions Prediction and Policy Analysis

<b>ERI</b>	Energy Research Institute
<b>ERIS</b>	Energy Research and Investment Strategy
<b>ETP</b>	Energy Technology Perspective
<b>ETSAP</b>	Energy Technology Systems Analysis Programme
<b>EU</b>	European Union
<b>FR</b>	France
<b>GDP</b>	Gross Domestic Product
<b>GEM-E3</b>	General Equilibrium Model for Economy, Energy, Environment
<b>GHG</b>	Greenhouse Gas
<b>GREEN</b>	GeneRal Equilibrium ENvironmental model
<b>HERMES</b>	Harmonized European Research for Macro sector and Energy Systems
<b>IAEA</b>	International Atomic Energy Agency
<b>IEA</b>	International Energy Agency
<b>IER</b>	Institute for Energy, Economic and Efficient Energy use
<b>IEJE</b>	Institut Economique et Juridique de l'Energie
<b>IFFS</b>	Intermediate Future Forecasting System
<b>IIASA</b>	International Institute for Applied Systems Analysis
<b>IKARUS</b>	Instruments for Reducing Greenhouse Gas Strategies
<b>IMAGE</b>	Integrated Model to Assess the Greenhouse Effect
<b>IPAC</b>	Integrated Policy Model for China
<b>IPAT</b>	environmental Impacts by the product of Population Affluence and Technology
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>JRC</b>	Joint Research Centre

<b>LC</b>	Low Carbon
<b>LEAP</b>	Long-range Energy Alternatives Planning
<b>LIMITS</b>	Low climate IMPact scenarios and the Implications of required Tight emission control Strategies
<b>LP</b>	Linear Programming
<b>MARKAL</b>	MARKet ALlocation model
<b>MEDEE</b>	Modèle D'Evolution de la Demande d'Energie
<b>MERGE</b>	Model for Evaluating the Regional and Global Effects of GHG Reduction Policies
<b>MESSAGE</b>	Model for Energy Supply Systems Alternative and their General Environmental Impact
<b>NEMESIS</b>	New Econometric Model of Evaluation by Sectoral Interdependency and Supply
<b>NEMS</b>	National Energy Modeling System
<b>NEWAGE</b>	National, European and Worldwide Applied General Equilibrium system
<b>NLP</b>	Non-Linear Programming
<b>OECD</b>	Organisation for Economic Co-operation and Development
<b>POLES</b>	Prospective Outlook on Long-term Energy Systems
<b>PRIMES</b>	Price Inducing Model of the Energy System
<b>RCP</b>	Representative Concentration Pathways
<b>RF</b>	Radiative Forcing
<b>RoSE</b>	Roadmaps towards Sustainable Energy futures
<b>SAGE</b>	System for the Analysis of Global Energy markets
<b>STIRPAT</b>	Stochastic Impacts by Regression on Population Affluence and Technology

<b>SVR</b>	Support Vector Regressions
<b>TIMES</b>	The Integrated MARKAL-EFOM System
<b>TPES</b>	Total Primary Energy Supply
<b>UNEP</b>	United Nations Environment Programme
<b>UNFCCC</b>	United Nations Framework Convention on Climate Change
<b>US</b>	the United States
<b>WEM</b>	World Energy Model
<b>WEO</b>	World Energy Outlook

# Chapter 1

## The Techno-Economic Modeling of Technology Roadmaps within the perspective of Climate Change

### 1.1 Introduction

Our research work<sup>1</sup> deals with the problems of modeling, assessing and proposing technology roadmaps for decarbonizing economic systems. We decided to do it for one developing country, China, and two developed countries, France and the United States, in order to fulfill the objective of reducing Greenhouse Gas (GHG) emissions in 2050. This period (from now until 2050) is consensually considered a transition period of our energy systems.

The technology roadmaps for certain GHG reduction targets are intended to be provided for policy makers, which are resulted from a new model introduced in this dissertation (our “Sectoral Emission Model”) which covers the main energy sectors with the principal energy technologies. This model offers technology roadmaps with different criteria, such as: i) the availability of energy resources and ii) the carbon equity.

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<sup>1</sup> This dissertation is carried out under the joint supervision of Jean-Claude Bocquet and Pascal Da Costa, at Laboratoire Génie Industriel (LGI), Ecole Centrale Paris, France.



We will justify all these points in this first introductory chapter:

- Firstly, we will introduce the research context: the climate change, especially the global warming and its driving forces: the anthropogenic GHG emissions, and particularly the CO<sub>2</sub> emissions from the fuel combustions (Section 1.2);
- Secondly, we will present the main concerns in the international debates, especially the carbon equity issue, and recent negotiations on climate change (Section 1.3);
- Thirdly, we will discuss the academic economic models with energy, and their advantages, defaults and results about the technology roadmaps for reducing CO<sub>2</sub> emissions (Section 1.4).

In the first chapter, we set forth:

- The problem setting and our research objectives (Section 1.5);
- And finally the plan of the thesis and the main results of each chapter (Section 1.6).

Let's begin with climate change and its driving forces.

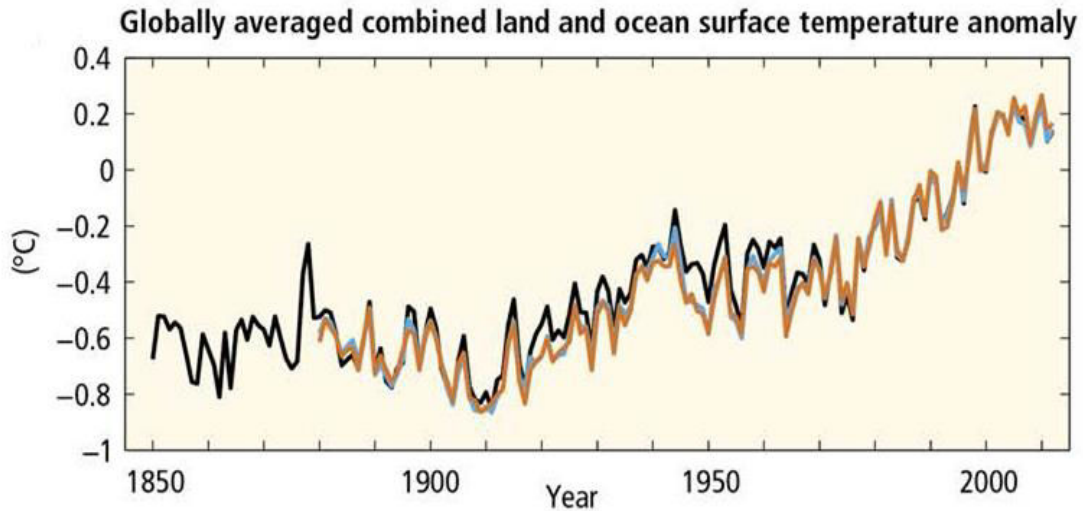
## **1.2 The Context of GHG emissions and Climate Change**

According to the Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC)<sup>2</sup>, the globally averaged combined land and ocean surface

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<sup>2</sup>The famous IPCC was set up in 1988 by the World Meteorological Organization and the United Nations Environment Program to provide governments with a clear view of the current state of knowledge about the science of climate change, potential impact, and options for adaptation and mitigation through regular assessments of the most recent information published in the scientific, technical and social-economic literature worldwide.

temperature had increased by 0.85 [0.65 to 1.06]<sup>3</sup>°C over the period from 1880 to 2012, as shown in the figure 1.1.



**Fig.1.1. Globally averaged combined land and ocean surface temperature anomaly<sup>4</sup> (IPCC, 2014b)**

As explained in the report of the second group of IPCC (2014c):

- “The changes in climate have caused impacts on natural and human systems on all continents and across the oceans. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality”.
- “Increasing global warming in the future will increase the likelihood of severe, pervasive, and irreversible impacts on the environment.”

The Earth’s climate is dependent upon the radiative balance of the atmosphere, which depends on the input of solar radiation and the atmosphere abundances of active traces gases (i.e. GHG), clouds and aerosols (IPCC, 2013). Increasing GHG emissions will absorb more radiation and prevent the radiation get out from the atmosphere. This

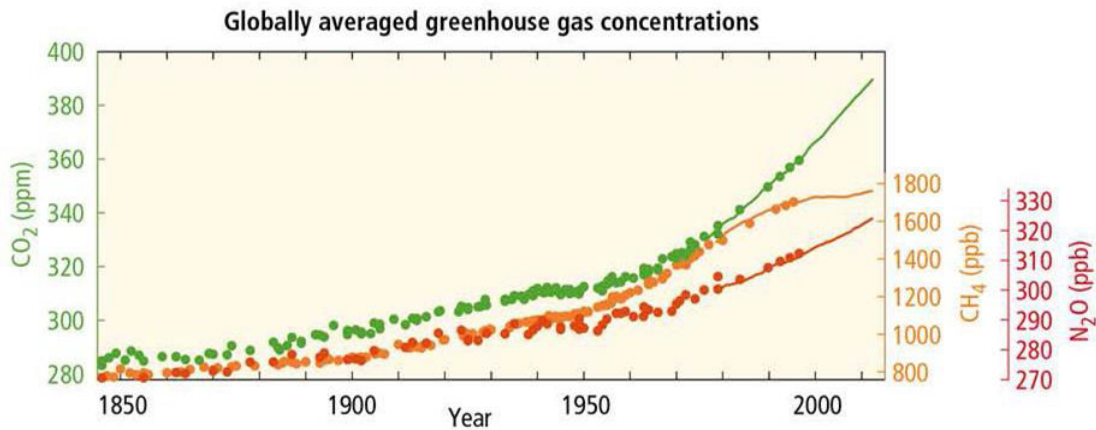
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<sup>3</sup> Ranges in square brackets are expected to have a 90% likelihood of including the value that is being estimated.

<sup>4</sup> The y-axis is the averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colors indicate different data sets (MLOST, HadCRUT4 and GISS).

is the so-called greenhouse effects.

Human activities are altering the Earth's atmospheric composition (Hansen et al., 2008). The steep increase in atmospheric concentrations of GHG emissions compared to the pre-industrial era have been detected throughout the climate system and are extremely likely to have been the dominant cause of observed warming since the mid-20th century (IPCC, 2014b). Actually, the anthropogenic GHG emissions since the pre-industrial era have driven large increase in the atmospheric concentrations of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, which are main factors behind global warming (Masson-Delmotte et al., 2015). The evolutions of these GHG emissions from 1850 to 2010 are shown in the figure 1.2.



**Fig.1.2. Globally averaged GHG concentrations (IPCC, 2014b)**

Different greenhouse gases have different Radiative Forcing (RF)<sup>5</sup>, which quantifies the change in energy fluxes caused by changes in the natural and anthropogenic drivers of climate change for 2011 relative to 1750. The most important factor in influencing the climate change is the CO<sub>2</sub> emission. Emissions of CO<sub>2</sub> alone have caused a RF of 1.68 [1.33 to 2.03] W m<sup>-2</sup>. Emissions of CH<sub>4</sub> alone have caused an RF of 0.97 [0.74 to 1.20] W m<sup>-2</sup>. And emissions of N<sub>2</sub>O alone have caused an RF of 0.17 [0.13 to 0.21] W m<sup>-2</sup> (IPCC, 2013).

Between 1750 and 2011, cumulative anthropogenic CO<sub>2</sub> emissions to the

<sup>5</sup> The unit of RF is watts per square meter (W m<sup>-2</sup>). It represents the change in energy flux caused by a driver.

atmosphere stand at  $2040 \pm 310$  GtCO<sub>2</sub>. About 40% of these emissions have remained in the atmosphere ( $880 \pm 35$  GtCO<sub>2</sub>). Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute decadal increases toward the end of this period, despite a growing number of climate change mitigation policies. In 2010, the global anthropogenic GHG emissions in 2010 have reached  $49 \pm 4.5$  GtCO<sub>2</sub>eq/yr<sup>6</sup> (IPCC, 2014b).

As the CO<sub>2</sub> emissions play the most important role in warming climate, we will focus on the CO<sub>2</sub> emissions in this work. There are principally two sources of CO<sub>2</sub> emissions, one coming from forestry and other land use, the other coming from fossil fuel combustion and industrial processes. CO<sub>2</sub> emissions from fossil fuel combustion and industrial processes are the primary source of anthropogenic CO<sub>2</sub> emissions, which contributed about 78% of the total GHG emission increase from 1970 to 2010 (IPCC, 2014b). Thus, we will focus on the CO<sub>2</sub> emissions from fuel combustion and industry processes in this work.

Obviously, economic and population growth remain the most important drivers of increases in CO<sub>2</sub> emissions from fossil fuel combustion (IPCC, 2014b). As the GHG emissions are shared by the entire world, it is necessary that all countries in the world make efforts to fight against the climate change. In the United Nations Conference on Environment and Development, an international treaty is negotiated with the objective of combining the climate policy among the parties, which will be presented in the following section.

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<sup>6</sup> GHG emissions are quantified as CO<sub>2</sub>-equivalent (GtCO<sub>2</sub>-eq) emissions, and  $\pm$  is expected to have a 90% likelihood of including the value that is being estimated.

## 1.3 The International Negotiations on the Mitigation of CO<sub>2</sub> and other GHG Emissions

The United Nations Framework Convention on Climate Change (UNFCCC) is the international environmental treaty set up by United Nations in 1992. Its Article 2 states its overall objective: “stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UN, 1992). Although this treaty sets does not set any limit on GHG emissions for individual countries, it provides a framework for negotiating specific international protocols that may set binding limits on GHG emissions.

Since 1995, the parties to the convention met annually in Conferences of the Parties (COP) to assess progress in dealing with climate change. In 1997, the Kyoto Protocol was ratified, establishing legally binding obligations for developed countries to reduce their GHG emissions<sup>7</sup>. The Kyoto Protocol has been endorsed by all the Annex I Parties<sup>8</sup> except the United States. The Kyoto Protocol has two commitment periods, the first of which lasts from 2005-2012, and the second 2012-2020. This Protocol is based on the principle of common but differentiated responsibilities, which sets higher reduction commitments to developed countries, consistently with their historically responsibility for the current levels of GHG in the atmosphere.

After the Kyoto Protocol, parties to the Convention have agreed to further commitments, including the Bali Action Plan (2007), the Copenhagen Accord (2009), the Cancún agreements (2010) and the Durban Platform for Enhanced Action (2012).

In the Bali Action Plan, all developed country Parties have agreed to “quantified

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<sup>7</sup> The Kyoto Protocol targets apply to four greenhouse gases, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), sulphur hexafluoride (SF<sub>6</sub>), and two groups of gases, hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

<sup>8</sup> Annex I Parties include the industrialized countries that were members of the Organisation for Economic Co-operation and Development (OECD) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States.

emission limitation and reduction objectives, while ensuring the comparability of efforts among them, taking into account differences in their national circumstances”. Its Article 3 (UN, 1992) states that “the Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities”. Developing country Parties agreed to “nationally appropriated mitigation actions in the context of sustainable development, supported and enabled by technology, financing and capacity-building, in a measurable, reportable and verifiable manner”.

The COP15 in Copenhagen was a crucial event in the negotiating process. In this negotiation, most countries agreed on the long-term goal of limiting the maximum global average temperature increase to no more than 2 degrees Celsius above pre-industrial level. There was, however, no consensus on how to do this in practical terms. 114 countries have ratified the Copenhagen Accord, and 17 developed country Parties and European Union have submitted mitigation targets, as well as 45 developing country Parties.

In the Cancún agreements in 2010, the objective of limiting global warming to 2°C were reaffirmed and many aspects of the Copenhagen Accord were brought in this agreement.

In the Durban Platform for Enhanced Action, all the parties agreed to “develop a protocol, another legal instrument or an agreed outcome with legal force under the Convention applicable to all Parties”. This new treaty is due to be adopted at the COP21 in Paris in 2015, and implemented in 2020.

In order to investigate the quantitative aspect of mitigation measures aimed at GHG reduction, energy-climate models have been developed with different aspects, which will be presented in the following section.

## 1.4 The Energy-climate Models and the Technology Roadmaps

Different models have been developed on the subject of the technology roadmaps related to the climate change issues, categorized by the approaches of top-down (e.g. CGE model), bottom-up (e.g. MARKAL model), and hybrid (e.g. POLES model). Each of the existing models has its own strengths and weaknesses, as discussed in some studies reviewing the literature on energy system models (Bhattacharyya and Timilsina, 2010; Fortes et al., 2013; Wei et al., 2006). The advantages of these models are that they are generally well developed, and cover the entire energy system with detailed technologies specification. However, this is difficult to add new technologies to these models. Besides, they generally require huge databases and advanced mathematical programming skills. Because the mechanisms and assumptions of the existing applied economic models can often be very different, it is very difficult to compare the results and understand well the numerous differences in predictions (Boulanger and Bréchet, 2005).

The future CO<sub>2</sub> emissions are difficult to be predicted. If the prediction is based on the evolution in the past, it provides only one direction, which is baseline scenario. However, the employment of scenarios with various assumptions can provide different directions of CO<sub>2</sub> emissions (Popiolek, 2015). Based on this consideration, CO<sub>2</sub> emissions scenarios are integrated into these models, such as the 2 degrees scenario, 4 degrees scenario, 6 degrees scenario in the WEO model (IEA, 2014), the Decarbonized scenario in the JRC-EU-TIMES model (Peteves et al., 2013), etc. The use of CO<sub>2</sub> emissions scenarios help the energy models to set the technology roadmaps in optimizing the total costs in different contexts, especially the energy technology adoption, the energy prices prediction, the energy policies, etc. However, another important issue in the climate change negotiations, carbon equity, is rarely considered in the modeling of technology roadmaps.

The carbon equity problem, often presented as the inequality of per capita emissions, has been under debate between developing and developed countries, as it

represents the different capacities and responsibilities for different countries (Heyward, 2007; Roberts, 2001; Yedla and Garg, 2014). However, this issue is often discussed in the CO<sub>2</sub> emissions budget allocation, which focuses on different allocation principles, as developing countries, for instance China, require larger emission space for economic growth than the developed countries, such as France and the United States. Carbon equity has not been involved in the study of the technology roadmaps for certain CO<sub>2</sub> emission scenarios. In this context, we propose our research objectives related to the carbon equity, as shown in the following section.

## **1.5 Our Problem Setting and our Research Objectives**

The purpose of this thesis is to assess the governmental targets in reducing the CO<sub>2</sub> emissions in 2050, for China, France and the United States. These governmental targets are as follows:

- In 2009, China promised to reduce its CO<sub>2</sub> intensity (CO<sub>2</sub> emission per unit of GDP) by 40%-45% in 2020 (ERI, 2009), and this objective is extenable to 85%-90% in 2050. In the “Plan for Climate Change (2014-2020)” (in Chinese) released in September 2014 by the Chinese government, this objective of reducing CO<sub>2</sub> emissions has not been changed. Besides, in the Asia-Pacific Economic Cooperation (APEC) in 2014, China has announced for the first time the intention to achieve the peaking of CO<sub>2</sub> emissions around 2030, according to the “China-US Joint Announcement on Climate Change” in November 2014.
- The French government announced the objective of reducing CO<sub>2</sub> emissions by 75% in 2050 compared to its level in 1990, which is named “facteur 4” (“loi N ° 2005-781 du 13 juillet 2005 de programme fixant les orientations de la politique énergétique (POPE)”)(ADEME, 2014). This objective of reduction has not been changed ever since.



- In June 2009, the U.S. House of Representatives passed the American Clean Energy and Security Act, which aimed to reduce 17% of their CO<sub>2</sub> emissions below the 2005 level in 2020, and 83% in 2050 (Waxman and Markey, 2009). During the APEC in 2014, the president Barack Obama promised to reduce CO<sub>2</sub> emissions by 26%-28% in 2025, as signed in the “China-US Joint Announcement on Climate Change”.

Based on these governmental targets in reducing GHG emissions, this dissertation mainly studies two research issues:

- 1) What measures could be taken in order to reach the CO<sub>2</sub> mitigation targets, consistently with each country’s particular situation and possible future changes?
- 2) How do the world technology convergences influence the energy transitions and the carbon equity?

In order to tackle these two issues, we set up a simple and flexible model covering the most important energy sectors for policy makers, which is different from the existing models based on the cost-effective approach. New technologies can be easily added into the model, and the technology roadmaps can be chosen according to different criteria. Meantime, we hope to add the carbon equity factor into the consideration of the technology roadmaps in the modeling, which means to propose the technology pathways in optimizing the carbon equity across sectors among different countries.

The plan of this dissertation is presented in the following section.

## **1.6 Plan, Research Methodologies and Main Results of the Thesis**

This doctoral dissertation is organized in five chapters:

- In Chapter 2: a detailed literature review on the energy-climate model, the

CO<sub>2</sub> emission scenarios and the carbon equity issues are presented, for the purpose of introducing the research development on the techno-economic modeling and the equity dimension on the climate change issue, which will be the basis of the research work in chapters 3 and 4.

- In Chapter 3: a new model, named “Sectoral Emission Model”, is introduced, which proposes different technology roadmaps in 2050 under different criteria for China, France, and the United States, in order to reach their governmental targets.
- In Chapter 4: an alternative technology roadmap is presented, in applying the carbon equity on the sectoral emissions under the assumption of convergence of technologies across sectors.
- The last chapter concludes and the perspectives of the work are discussed.

In our Sectoral Emission Model, extensive data are not required. This model decomposes the energy system into three main energy sectors: Power sector, Transport sector, and “Other sectors”, which includes residence, industry, and the rest sectors. The power, transport, residence and industry sectors are responsible for more than 80% of the CO<sub>2</sub> emissions in 2010 in China, France and the United States.

The energy-related technologies considered in this work are mainly the technologies in the power and transport sectors, as they stand as the principal sources of CO<sub>2</sub> emissions. Energy mix changes, Carbon Capture and Storage (CCS), electric vehicles adoptions and improvement of energy efficiency are the parameters we focus on in terms of CO<sub>2</sub> emission reduction in the modeling.

We apply this model to three types of country that may be considered as representatives of a number of other similar countries in the world: China (CN) is a fast-growing, emerging economy that requires increasing energy consumption; France (FR) is a well-developed economy with relatively low CO<sub>2</sub> emissions; and the United States (US) is both the largest economy and a major source of CO<sub>2</sub> emissions.

The structure of the model for each country is as follows. In the modeling of the power sector, energy mix and CCS are the two main technologies considered, while

fossil fuels such as coal, oil and gas are the three main sources of CO<sub>2</sub> emissions in the power sector.

If the prevalence of fossil fuels is not to be put into question, CCS will be one of the potential options for reducing atmospheric emissions of CO<sub>2</sub> from power plants.

Besides, the CO<sub>2</sub> emission intensity of production (CO<sub>2</sub> emissions per KWh from electricity generation) and electricity output are two important factors in the model. For robust predictions, we use the Support Vector Regressions (SVR) method dedicated to non-linear regressions (Cortes and Vapnik, 1995) to simulate future electricity production. The method has proved to be an appropriate model for electricity load forecasting (Hong, 2010; Wang et al., 2009) with a small database. For the CO<sub>2</sub> emission intensity of production, we assume that our three countries in 2050 emit as much CO<sub>2</sub> per unit KWh as European countries were emitting in 2010, as these represent the lowest emission of production in the world in 2010.

The power generation sector makes the most important contribution to the global CO<sub>2</sub> emissions, and the second most important emitter is the transport sector, of which 72% CO<sub>2</sub> emissions come from road transport. Thus, we will focus on the emissions from the road transport in the transport sector emissions, as they are the most important emission source in the transport sector. The key technology in the road transport proves to be the electric vehicles. However, as the use of electric vehicles requires more electricity consumptions, the numbers of electric vehicles are taken into account in the electricity production in the power sector.

Amongst the “Other sectors”, we consider primarily domestic and industrial consumption because these two sectors account for most of emissions in this sector. Improving energy efficiency is the key technology and best strategy for reducing CO<sub>2</sub> emissions in the two sectors.

In this work, our objective is to propose technology pathways in order to meet the CO<sub>2</sub> emission reduction targets for China, France and the United States. We develop five scenarios served as reference scenarios: Business-as-Usual (BaU) scenario, 2°C and 3°C scenarios from IPCC with two allocation approaches: grandfathering and equal emission convergence.

For the simulation of BaU scenario for each country, the Stochastic Impacts by Regression on Population Affluence and Technology (STIRPAT) model is employed. STRIPAT was preferred for IPAT (which assumes the environment Impact is the results of Population, Affluence and Technology) since it statistically models the non-proportionate impacts of variables on the emissions (see works from (Dietz and Rosa, 1994, 1997; Lin et al., 2009; Martinez-Zarzoso and Maruotti, 2011; Meng et al., 2012; Squalli, 2010; Wei, 2011; York et al., 2003))

All possible solutions for the technology pathways can be generated with our Sectoral Emission Model, offering the policy makers choices of technology transition solutions according to their different criteria. Besides the solution pool of the technology roadmaps, we provide two roadmaps for two criteria: one for balanced technology development across sectors, and the other for least changed energy mix.

The results show that the governmental targets in France and the United States are very strict, which require all sectors to make large efforts in reducing CO<sub>2</sub> emissions. However, the governmental target in China is more tolerant, where the advancement of technologies is less demanding than in France and the United States. If the energy mix is expected to be kept unchanged in China and in the United States, the CCS is required to be implemented to all power plants.

The sensitivity test of parameters in the model for different technology roadmaps in different countries shows that the electricity output and the emission intensity of production are the two parameters with the most important influence on CO<sub>2</sub> emissions. Thus, improving the efficiency of coal combustion and the energy efficiency of electricity will play important roles in the emission reductions.

These technology roadmaps are obtained without neither the cost constraint nor the equity constraint. However, we believe that with the share of technology development in the world, there will be a convergence of technologies in each energy sector. Under this assumption, we propose an optimization method to minimize per capita emissions inequality across the three main energy sectors among the three countries. The Theil index is chosen to be our measurement of inequality of per capita CO<sub>2</sub> emissions, and the Differential Evolution methodology is used to carry out the carbon equity optimization for multiple objectives.

The optimization of sectoral per capita emissions equity is based on our Sectoral Emission Model. We aim to find the technology pathways in the context of realizing the best equity of per capita emissions across sectors under certain emissions scenarios by introducing a benchmark nation, here France in this work. First of all, per capita emissions level is relatively low in France compared to other developed countries<sup>9</sup>. Besides, its per capita CO<sub>2</sub> emission in the power sector is low, relative to that in the United States and China. Then we hope to find pathways through converging the per capita emissions to France for the most two important emitters: China and the United States, in achieving their governmental targets.

The results show that in order to achieve the governmental target, coal combustion should be reduced by two thirds in China, and the coal should be almost eliminated in the United States. However, gas is encouraged to be used in the power sector, especially in the United States. Regarding the transport sector, more than 60% of vehicles should be replaced to electric vehicles in China, and this share will be about 90% in France and the United States. In the residence and industry sector, the energy efficiency should be improved by about 50% in China and France, 70% in the United States. Regarding the sensitivity of the models with respect to the parameters, it shows that the most important parameter is electricity output for all the three countries. The CO<sub>2</sub> emission of production of coal in China and that of gas in the United States also play an important role in influencing the CO<sub>2</sub> emissions. Because a large share of vehicles are expected to be changed to electric vehicles in these countries, the parameters in the power sector becomes more important to meet the governmental reduction targets while at the same time reducing sectoral carbon inequality.

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<sup>9</sup> In 2010, the per capita CO<sub>2</sub> emissions from fuel combustions in France is 5.52 tonnes, which is about half of the mean level in OECD countries.

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# Chapter 2

## Literature review: a summary of energy system models and carbon inequality articles

### 2.1 Introduction

In the international climate negotiations<sup>10</sup> organized by the United Nations, the cost effectiveness of the mitigation plans and the carbon equity across countries are two main issues the most discussed. Since 2000s, numerous energy-economic-environmental models have been developed to work on the future Greenhouse Gas (GHG) emissions scenarios and the cost-effective mitigation options. And then the carbon equity problem came along, especially for the developing countries who indicated that their priorities lied with continued economic growth, and that they had a “right” to increase emissions to meet development needs. Any future agreement that does not acknowledge - and seek to formally address - this concern is unlikely to meet with political success in an international forum (Philibert and Pershing, 2001).

In this chapter, we will review the energy-economic-environmental models, the

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<sup>10</sup> The international climate negotiations cited in this work refer to the Conference of the Parties (COP), e.g. COP3 in Kyoto in 1997, COP15 in Copenhagen in 2009, COP20 in Lima in 2014, etc.

CO<sub>2</sub> emission scenarios settings, and the main carbon equity studies. Three issues which are strongly entangled in international climate negotiations and prove to be too separated at academic and applied research.

Concerning the energy-economic-environmental models, there are basically three categories of approaches: top-down model, bottom-up model and hybrid model. These models study the energy system from economic or technologic aspects, which cover the entire energy system and require the complete and exhaustive technologies specifications. However, we will see that the extensive data and high level of mathematical programming skills make it difficult to add other criteria. Besides, the top-down models and bottom-up models often conduct different results, as the bottom-up models are likely to be less costly than the top-down models (Fortes et al., 2009).

Different CO<sub>2</sub> emission scenarios are integrated with these models, in the worldwide, regional, and national level. The economic factors are often considered in the CO<sub>2</sub> emission scenarios, as well as the technology development, population evolution. But the energy-economic-environmental models and the CO<sub>2</sub> emission scenarios study the technology pathways only for the cost-effective objective, where the carbon equity is very rarely considered. There appear to be no univocal solutions to the dual objective of efficiency and equity. Actually, the carbon equity is often discussed on the CO<sub>2</sub> emission allocations between countries or regions, and on its driving forces.

The carbon equity has rarely been considered as a criterion in the decision on the technology roadmaps: carbon inequality is generally discussed on the international, regional, or sub-national level, rarely discussed on the energy sector level. That is why we will discuss the current literature of each of the dimension (e.g. the energy-economic-environmental models, the CO<sub>2</sub> emission scenarios settings, and the carbon equity studies), before developing in the following chapters of this thesis our own models that offer an analytical framework to connect the latter three dimensions.

There are numerous energy-climate models and CO<sub>2</sub> emission scenarios. Here in this chapter, we select the most commonly used models and the relative CO<sub>2</sub> emission scenarios to present. The CO<sub>2</sub> emission scenarios for China, France and the United States will also be presented since they are the objective countries in this dissertation. The differences between these studies and our works in the rest of the dissertation will

be compared in details in Chapter 3 and Chapter 4.

The plan of this chapter is organized like following:

- In section 2.2, the energy systems models are summarized by three approaches: top-down, bottom-up, and hybrid.
- In section 2.3, the CO<sub>2</sub> emission scenarios from different institutes and models are introduced.
- In section 2.4, we will explain the carbon equity principles and its measurement index.
- The last section concludes.

## **2.2 Energy-economic-environmental models**

In response to the need of evaluating the impacts of GHG reduction for nations, regions and the world, energy-economic-environmental models are developed to outline how the transition to a low-carbon economy can be achieved and how to assess its economic impacts. Macro-economic top-down and technological bottom-up frameworks are two basic modeling approaches in the energy system modeling.

Top-down models analyze aggregated behaviors based on economic indices of price and elasticity. These models began mainly as macroeconomic models that tried to capture the overall economic impact of a climate policy, which, because of the difficulty of assessing other types of policy instruments, were usually in the form of a carbon tax or tradable permits. Bottom-up models, on the other hand, rely on the detailed analysis of technical potential, focusing on the integration of technology costs and performance data. Hybrid models are set in order to merge top-down and bottom-up models, which includes variables of the economy, supply, conversion, demand, environment, module,

plus additional country specific considerations (IPCC, 1996).

In this section, the most typical economic-energy-environmental models are categorized into the three families: top-down, bottom-up and hybrid models. Their specifications and applications are now presented.

## **2.2.1 Top-down model**

The top-down models are most used in the energy policy assessments. They describe the interaction between energy system and the economy as a whole, maximizing the utility of the economic agents as a sequence of optimal saving, investment, and consumption decisions.

In this section, we will first present the Computable General Equilibrium models for energy in general, and then principally three famous top-down models: the GEM-E3 model, the 3Es model, and the MACRO model.

### **➤ The Computable General Equilibrium model for energy**

Norwegian economist Johnsen first established the Computable General Equilibrium (CGE) models in 1960. The CGE models focus on energy were developed in 1980s, which simulated interactions among variables of energy, economy and environment.

The model constructs the behavior of economic agents based on microeconomic principles, and it typically simulates markets for factors of production (e.g. labor, capital, and energy), products and foreign exchange, with equations that specify supply and demand behaviors. Many countries have set their own CGE model, which bring an obvious advantage in the energy trade, energy environment and tax policy analysis (IPCC, 2001; Wei et al., 2006).

For instance:

- Kumbaroglu (2003) designed a CGE model for macro-economy, energy

and environment in Turkey and studied sustainable problems of ecology and economy in different carbon tax scenarios.

- Galinis and Van Leeuwen (2000) used a CGE model in order to analyze how Holland would adjust nuclear development policy and strategy in the future under different economic developments, energy prices and potential uses for nuclear development scenarios.
- Zhang (2000; 1998), Zhang and Folmer (1998), and Zhang and Baranzini (2004) established a dynamic CGE model, and studied the macro-economic and sector impacts of CO<sub>2</sub> emissions abatement in China.

### ➤ **The GEM-E3 model**

The General Equilibrium Model for Economy, Energy, Environment (GEM-E3) is a recursive dynamic CGE model that covers the interactions between the economy, the energy system and the environment. It is especially designed to evaluate environmental policies (in particular GHG emission reduction policies). GEM-E3 can evaluate consistently the distributional effects of policies for the various economic sectors and agents across countries. There are two versions of GEM-E3: GEM-E3 Europe and GEM-E3 World. They differ in their geographical and sectorial coverage, but the model specification is the same.

For instance:

- Bahn (2001) used the GEM-E3 model to research how to constitute a combining policy instrument, and to develop a policy to show how to impact on macro-economics in Switzerland by identifying a correct national carbon emission trade off.
- Saveyn et al. (2011) used the GEM-E3 to assess the economic consequences of the climate ‘Copenhagen Accord’.
- And Saveyn et al. (2012) used the GEM-E3 to study the economic implications of different global GHG emission mitigation policies on the

major Asian economies: China, India and Japan.

- Pralong, Van Regemorter, Zagamé (2003) used GEM-E3 to study the way the carbon market was designed after Kyoto 1998, with the impact on the States of the Former Soviet Union and Eastern Europe that were likely to become large sellers of carbon as a result of the drop in emissions level due to economic downturn, referring to "Hot Air".

### ➤ **The 3Es model**

The 3Es model is an integrated econometric model developed by Nagaoka University of Technology in Japan, which involves macroeconomic model, energy model and environment model. It was used to simulate the relationship of macroeconomic, energy and environment, and to forecast the trend of the economy, energy and environment, under the scenarios of saving, carbon tax and improvement in energy efficiency. The resultant output of the model provided information for decision makers when planning the long-term energy tactic and policy.

For instance, Li (2003) established a 3Es model using the econometric approach for simulating economy, energy and environment of China to 2030.

### ➤ **The MACRO model**

The MACRO model is a macro-economic module of the macro-economic model MERGE (a Model for Evaluating the Regional and Global Effects of GHG Reduction Policies) (Manne and Richels, 1992). It describes the relationship of energy consumption, capital, labor force, and GDP by production function with an aggregated view of long-term economic growth. Its objective function is the total discounted utility of a single representative producer-consumer realized by non-linear optimization. The maximization of this utility function determines a sequence of optimal savings, investment, and consumption decisions.

The MACRO model is modified to integrate with some bottom-up models: such as,

the MESSAGE model (MESSAGE-MARCO), the EFOM model (EFOM-MARCO) and MARKAL model (MARKAL-MARCO).

For instance:

- Lim et al. (1998) used the EFOM-MACRO model to study the role of nuclear energy in the Korean sustainable energy system, under various scenarios with differing carbon tax rates.
- Chen (2005) used an integrated energy-environment-economy model to analyze China's marginal abatement cost of carbon, the rates of GDP losses and the changes of abatement rate in carbon emission.
- Papatheodorou (1990) focused on production function, energy demand function and energy prices in a MACRO model that was used to analyze the role of energy for Greece's economy.

### ➤ **Other top-down models**

Besides the models above, there are other top-down models, such as the General Equilibrium Environmental model (GREEN) that was developed by the OECD (Oliveira Martins et al., 1992) and the National, European and Worldwide Applied General Equilibrium system (NEWAGE) developed by the Institute for Energy, Economic and Efficient Energy use (IER) in Stuttgart University in Germany, the Harmonized European Research for Macro sector and Energy Systems (HERMES) developed by the European Union (EU) (Bossier and De Rous, 1992), the New Econometric Model of Evaluation by Sectoral Interdependency and Supply (NEMESIS) model developed in the Ecole Centrale Paris and for the EU (Da Costa et al., 2009), etc.

Top-down models analyze the energy system from the macro-economic perspective, in considering the energy price and elasticity. Nevertheless, these models do not contain rich technological details representing the energy sector in aggregated form by production functions which capture substitution possibilities through elasticity of substitution (Böhringer, 1998).



In the next sub-section 2.2.2, the bottom-up models, which focus on the technology performance and advancement, will be presented.

## **2.2.2 Bottom-up model**

Different from the top-down models, the bottom-up models generally follow a partial equilibrium representation of the energy system, describing it in great details in a form of technology matrix containing current and future technologies (Fortes et al., 2009).

In this section, six most commonly used bottom-up models will be presented: the EFOM-ENV model, the MARKAL family models, the LEAP model, the MEDEE model, the AIM model, and the MESSAGE model.

### **➤ The EFOM-ENV model**

The Energy Flow Optimization Model-ENVironment (EFOM-ENV) is an EU model that has been used in national energy system studies for all EU countries. It is a Linear Programming (LP) model, which covers the complete energy systems of a country. It was developed upon the EFOM model which was initially developed in the 1970s by Finon (1974) at the “Institut Economique et Juridique de l’Energie” (IEJE) in France, and then used in the world (Pilavachi et al., 2008; Sadeghi and Mirshojaieian Hosseini, 2008).

The EFOM-ENV model is widely used to evaluate new technologies, and to assess energy and environmental policies, minimizing total energy system cost given the demands for effective energy services and commodities.

For instance, some uses:

- Remmers et al. (2004) demonstrated the methodology for integrating emissions reduction technologies into the EFOM-ENV model.
- Plinke et al. (1992) applied the EFOM-ENV model to energy strategies to

control pollutants emissions for Turkey, and analyzed cost efficient emission control strategies for the Turkish energy system.

### ➤ **The MARKAL family models**

**The MARKAL model:** MARKet ALlocation model (MARKAL) is a widely applied bottom-up, dynamic, originally and mostly a LP model developed by the Energy Technology Systems Analysis Programme (ETSAP) of International Energy Agency (IEA).

MARKAL depicts both the energy supply and demand side of the energy system, and it provides policy makers and planners in the public and private sectors with extensive details on energy producing and consuming technologies, and an understanding of the interplay between the macro-economy and energy use (Seebregts et al., 2002).

This model is implemented in more than 40 countries and by more than 80 institutions. For instance:

- Naughten (2003) used the MARKAL model to evaluate the competitive advantage and position of natural gas fired combined cycle gas turbines when compared with coal fired generation in the energy sector in Australian competing electricity markets.
- Gielen and Changhong (2001), applied the MARKAL model to study optimal strategy for GHG abatement of energy system in Shanghai during the period 2000-2020.
- Sato et al. (1998), analyzed the potential for reducing CO<sub>2</sub> emissions and identified important energy and technology options in future energy systems of Japan.
- Larson et al. (2003) built a model of China's energy system based on MARKAL energy-system modeling tool and analyzed choices of energy technology in different scenarios for China while it continues its social and economic development (and ensuring national energy supply security

and promoting environmental sustainability).

- Rydén et al. (1993) described community energy systems in five Swedish communities using the IEA-MARKAL, and evaluated the role of different technologies in producing district heat compared combined heat and power (CHP) with other technologies.

**The TIMES model:** The Integrated MARKAL-EFOM System (TIMES) is an economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon.

It is usually applied to the analysis of the entire energy sector, but may also applied to study in detail singles sectors (Loulou et al., 2005). TIMES computes a dynamic inter-temporal partial equilibrium on integrated energy markets. The objective function to maximize is the total surplus. This is equivalent to minimizing the total discounted system cost while respecting environmental and many technical constraints. This cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon, plus the welfare loss due to endogenous demand reductions (Vaillancourt et al., 2008).

Some examples of applications of the TIMES model:

- Vaillancourt et al. (2008) used the World-TIMES model to analyze the role of nuclear energy in long-term climate scenarios for the energy system of 15 regions between 2000 and 2100.
- Blesl et al. (2007) applied the TIMES model to examine the impacts of additional efficiency improvement measures on the German energy system in terms of energy savings, technological development, emissions and costs.
- The Joint Research Centre (JRC) of European Commission has developed the JRC-EU-TIMES model to analyze the role of energy technologies and their innovation for meeting Europe's energy and climate change related policy objectives (Da Camara et al., 2013).

***The MARKAL-MACRO model:*** In the MARKAL family, the MARKAL-MARCO (Manne and Wene, 1992) is an integrated model of the bottom-up MARKAL model with its detailed and explicit technological representation, and of the top-down MARCO model (Manne and Richels, 1992), a succinct, single sector, optimal growth dynamic inter-temporal general equilibrium model, based on the maximization of a national utility function.

Merging these two models results in a new model that captures the characteristics of an inter-temporal general equilibrium model, while retaining the rich technological details of MARKAL (Loulou et al., 2004). This integrated model is a Non-Linear Programming (NLP) model. Thus it can be considered as a hybrid model.

Other examples of applications:

- Chen et al. (2007) used MARKAL family model (MARKAL, MARKAL-MARCO and MARKAL-ED (elastic-demand)) to study China energy system's carbon mitigation strategies and corresponding impacts on the Chinese economy.
- Nystrom and Wene (1999) applied the MARKAL-MARCO model on three important policy issues in the Swedish energy system restriction of CO<sub>2</sub> emissions, phasing out of nuclear power, and the availability of energy conservation.

***The MARKAL-MICRO model:*** The MARKAL-MICRO is similarly an integrated NLP model, which is an alternate partial equilibrium formulation of MARKAL that allows endogenous, price sensitive useful energy demand, jointly with the price sensitive supply of energy (Van Regemorter and Goldstein, 1998). One difference between the two versions is that MARKAL-MICRO accepts cross-price elasticity of demand (i.e. a decrease in the relative price of passenger rail transport may reduce the demand for automobile traffic accompanied by a shift to rail transport), whereas "standard MARKAL" accepts only own-price elasticity. Cross price elasticity allow inter-demand substitutions, as for example between passenger car transport and mass transit (Loulou et al., 2004).

## ➤ **The LEAP model**

The Long-range Energy Alternatives Planning (LEAP) model is a flexible modeling environment that allows building-specific applications suited to particular problems at various geographical levels: cities, state, country, region or world. The model follows the accounting framework to generate a consistent view of energy demand (and supply) based on the physical description of the energy system.

LEAP is not a model of a particular energy system, but rather a tool that can be used to create models of different energy systems, where each requires its own unique data structures. LEAP supports a wide range of different modeling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling. LEAP also includes a range of optional specialized methodologies including stock-turnover modeling for areas such as transport planning.

On the supply side, LEAP provides a range of accounting and simulation methodologies that are powerful enough for modeling electric sector generation and capacity expansion planning, but which are also sufficiently flexible to allow LEAP to incorporate data and results from other more specialized models (Bhattacharyya and Timilsina, 2010).

Examples of applications:

- Kumar et al. (2003) assessed the GHG abatement effects and potential of biomass energy technologies in Vietnam's energy system under alternative scenarios.
- Shin et al. (2005) analyzed the impacts of the expansion of landfill gas electricity generation capacity on the energy market, the cost of generating electricity and GHG emissions in Korea.
- Bose and Srinivasachary (1997) analyzed factors influencing energy consumption pattern and emission levels in the transport sector of Delhi; and extrapolated total energy demand and the vehicular emissions using the model LEAP and the associated 'Environmental Database'.
- Bala (1997) studied rural energy supply and demand and assessed the

contributions to global warming for Bangladesh with LEAP, due to the shortcomings of traditional uses of biomass fuels in rural areas.

### ➤ **The MEDEE model**

The MEDEE ('Modèle D'Evolution de la Demande d'Energie') was developed by B. Château and B. Papilloné at IEJE in France in 1980s. It is a long-term demand prospective national model for a given market, with considerable parameter flexibility to build scenarios.

Since 1978, MEDEE-2 was implemented at International Institute for Applied Systems Analysis (IIASA) in order to evaluate the energy demand, region by region, and the economic, technical, and lifestyle factors (Lapillonne, 1978). After then, the International Atomic Energy Agency (IAEA) adopted MEDEE-2 model and incorporated important modifications to make it more suitable for application in developing countries, named as the MAED model (IAEA, 2006).

Examples of applications of the MEDEE model:

- Lapillonne (1980) forecasted the energy demand in the USA for the 1985-2000 period based upon three scenarios.
- Messenger (1981) using the MEDEE model analyzed that changes in the structure and energy intensity of the Western European economy are projected in response to increases in real energy prices.
- Lapillonne and Chateau (1981) introduced the method and system of the model MEDEE and estimated future energy demand.

### ➤ **The AIM model**

The Asian-Pacific Integrated Model (AIM) is a large-scale computer simulation model developed by the National Institute for Environment Studies in Japan in 1994. It aims to assess policy options for stabilizing the global climate, particularly in the Asian-

Pacific region, with the objectives of reducing the GHG emissions and avoiding the impacts of climate change (Matsuoka et al., 1995).

The AIM model comprises three main models:

- A GHG emissions model (AIM/Emission);
- A global climate change model (AIM/Climate);
- And a climate change impact model (AIM/Impact).

The AIM/Emission model includes data and information on population, economic trends, and government policies, and estimates energy consumption, land use changes, and GHG emissions. Then the AIM/Climate model examines the outcome of different policy scenarios. Finally the AIM/Impact model estimates impacts of the various scenarios on primary production industries and human health.

As the Asia-Pacific region has half of the world's population and is experiencing very rapid economic growth, it plays an important role in the global climate change issues. That is why there are numerous examples of applications of this model, such as:

- Jiang et al. (2000) analyzed long term GHG emission scenarios depending on alternative development paths in the developing countries of this region.
- Matsuoka et al. (1995) categorized the scenarios that have been written about so far in relation to global warming. Then they simulated the effects of global warming, taking into account various uncertainties, which ultimately described several outcomes from the AIM/impact model.
- Kainuma et al. (2000) predicted GHG emissions and evaluated policy (carbon tax or subsidies) measures to reduce them with two socioeconomic scenarios.

### ➤ **The MESSAGE model**

The Model for Energy Supply Systems Alternative and their General

Environmental Impact (MESSAGE) was developed by the IIASA in Austria since the 1980s (Messner and Strubegger, 1995). MESSAGE is a system engineering optimization model used for the planning medium- to long-term energy planning, energy policy analysis and scenario development, for national or global regions.

The model's principal results are the estimation of global and regional, multi-sector mitigation strategies instead of climate targets. MESSAGE allows determining cost-effective portfolios of GHG emission limitation and reduction measures.

MESSAGE was used to develop global energy transition pathways together with the World Energy Council (Nakićenović et al., 1998) and IPCC (Grübler et al., 2007).

Some examples of improvements of the model:

- Gritsevskiy and Nakićenović (2000) introduced a method for modeling-induced technological learning and uncertainty in energy systems, and three related features of the energy systems-engineering model MESSAGE, that studied energy technologies choices for varying future scenarios.
- Messner et al. (1996) introduced an approach to modeling the uncertainties concerning the future characteristics of energy technologies within the MESSAGE framework of long-term dynamic linear programming models.
- Dayo and Adegbulugbe (1988) used the energy supply model MESSAGE II to show that an optimal structure of Nigeria's energy system should lead to a 19-fold increase in the utilization of the gas resources between 1980 and 2010.

### ➤ **Other bottom-up models**

In addition, there are other typical bottom-up models, such as ERIS (Energy Research and Investment Strategy) model developed by the European Commission (Kypreos et al., 2000), EPPA (Emissions Prediction and Policy Analysis) model developed by the Massachusetts Institute of Technology (Paltsev et al., 2005) and



IKARUS (Instruments for Reducing Greenhouse Gas Strategies) developed by IER (Katscher, 1993).

The bottom-up models presented in this section offer an integration of detailed energy related technologies. The bottom-up models solve optimization problems, computing the least-cost combination of energy technologies to meet energy service demand subject to several restrictions (e.g. emissions, technologies availability, energy sources potential). However, the bottom-up models neglect the interactions of the energy sector with the rest of the economy, ignoring the macro-economic feedbacks of different energy system pathways induced by the climate policies (Fortes et al., 2009).

In this consideration of the integration of the bottom-up models and top-down models, hybrid models are proposed. In the next sub-section 2.1.3, the typical and often used hybrid models are presented.

### **2.2.3 Hybrid models**

The hybrid model was firstly introduced by Parikh (1981) as an integrated model for energy system analysis, aiming to connect the macro-economic element with a detailed end-use-oriented energy sector description. The specific strengths and weaknesses of the bottom-up and top-down approaches explain the wide range of hybrid modeling efforts that combine technological explicitness of bottom-up models with the economic comprehensiveness of top-down models (Hourcade et al., 2006).

There are various hybrid modeling efforts that aim at combining the technological explicitness of bottom-up models with the economic richness of top-down models (Böhringer and Rutherford, 2006).

Here in this section, six most commonly used hybrid models: the NEMS model, the POLES model, the WEM model, the SAGE model, the IPAC model, the IMAGE model, will be presented.

### ➤ **The NEMS model**

The National Energy Modeling System (NEMS) was designed and primarily used by the US Department of Energy for preparing the Annual Energy Outlook (AEO) (EIA, 2014, 2015). This hybrid model of energy-economy interactions is used to analyze the functioning of the energy market under alternative growth and policy scenarios.

The model employs a technologic rich representation of the energy sector and covers the spatial differences in energy use in the USA. The demand-side is disaggregated into four sectors, namely industry, transport, residential and commercial but both industry and transport are further disaggregated to capture the specific features of energy intensive users and alternative modes of transport. The supply-side of the model contains four modules – one each for oil and gas supply, gas transportation and distribution, coal supply and renewable fuels. There are two conversion modules, namely for electricity and petroleum product markets. These modules consider the technological characteristics of electricity supply and refining.

Two examples of applications with:

- Hadley and Short (2001) used CEF-NEMS (Scenarios for a Clean Energy Future) model which examines the impact of policies on CO<sub>2</sub> and other air emissions reductions in the electric sector of America.
- Wilkerson et al. (2013) used NEMS model for the projection of energy demand in the residential and commercial sector in the USA.

### ➤ **The POLES model**

The Prospective Outlook on Long-term Energy Systems (POLES) is a recursive, disaggregated global model of energy analysis and simulation that has been used for long-term energy policy analysis by the EU and the French government.

The model has four main modules: final energy demand, new and renewable energy technologies, conventional energy transformation system and fossil fuel supply. Accordingly, the model captures the entire energy system. The demand is analyzed

using a disaggregated end-use approach with separate treatments of energy intensive and non-intensive uses. The global demand is generated from national and regional demands. Criqui et al. (1999) using the POLES model, evaluate the stakes and economic potential of adopting a tradable emission permit system, both for those countries that made a commitment in Kyoto and for developing countries.

And:

- Criqui and Mima (2001) provided some insight on the issues raised by the tradable emission permit system proposed in a Green Paper of the EU in 2000, using POLES-ASPEN.
- Russ and Criqui (2007) used the POLES model to analyze the impact of emission reduction on the structure on the future of the energy system in a worldwide level.

### ➤ **The WEM model**

The World Energy Model (WEM) used in the World Energy Outlook (WEO) of IEA is a global energy market model for medium to long-term energy projections. It is designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by region projections for various scenarios.

The model consists of six main modules: final energy consumption (with sub-models covering residential, services, agriculture, industry, transport and non-energy use); power generation and heat; refinery/petrochemicals and other transformation; fossil-fuel supply; CO<sub>2</sub> emissions and investment (IEA, 2011b).

### ➤ **The SAGE model**

The System for the Analysis of Global Energy markets (SAGE) is a specialized version of MARKAL adapted for use by the US Department of Energy's Energy Information Administration, as the analytic foundation for the annual publication of the

International Energy Outlook. The SAGE variant of the MARKAL family was conceived to introduce new behavioral elements into the model's partial equilibrium paradigm (Loulou et al., 2004).

The main two differences between SAGE and MARKAL are first that SAGE is run in a time-stepped manner, that is myopically solving for each model period in sequence, whereas MARKAL employs perfect foresight as it clairvoyantly solves for the entire modeling horizon at once, and second that SAGE employs a market sharing algorithm that modifies the least cost criterion used by MARKAL.

SAGE also has available a technology learning component similar to MARKAL, but with one important difference due to the near-sighted nature of the model. SAGE adjusts the investment cost between each period based upon the cumulative capacity thus far installed for technologies with learning. Indeed, without the look-ahead capability of MARKAL, SAGE cannot anticipate the need to invest early in such technologies so the learning mechanism is only of a truly endogenous nature (Bhattacharyya and Timilsina, 2010).

## ➤ **IPAC model**

The Integrated Policy Model for China (IPAC) model was developed by the Energy Research Institute (ERI) of China. It is a multi-model framework, which covers different modeling methodologies by focusing on various policy questions.

The IPAC model includes global model, national model and regional models. There are two global models in IPAC, one is IPAC-TIMER model which originally come from IMAGE model, and the other one is IPAC-Global model, which was developed in the IPCC SRES scenario development process, and it will be used in the Roadmaps towards Sustainable Energy futures (RoSE) study. National models cover CGE model, technology simulation model. The provincial model or regional model is using same model with national one of technology simulation, which cover all provinces in China.

Besides, in order to support low carbon development in cities, city level

technology models were developed. Jiang et al. (2013) used the linked IPAC models (IPAC-Asia Integrated Model (AIM)/technology and IPAC-second generation model (SGM) national models) to provide a quantitative analysis that covers both global emissions and China's national emissions.

In order to analyze the feasibility of China in attaining the 2°C target and the related emissions pathway and options, the IPAC-Emission global model was firstly used to estimate the levels of global emissions up to 2100 (to reach the 2°C target), and then to analyze the emissions in China in the global context. After that, the results are used in the IPAC-AIM/technology and IPAC-SGM national models to evaluate China's options in obtaining the 2°C target.

## ➤ **IMAGE**

The Integrated Model to Assess the Greenhouse Effect (IMAGE) model is an Integrated Assessment Model (IAM) which is often used for the IPCC assessments. It was developed by PBL Netherlands Environmental Assessment Agency to simulate the environmental consequences of human activity worldwide. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result from interacting demographic, technological, economic, social, cultural and political factors (Stehfest et al., 2014).

The IMAGE model has been used for various purposes in different studies, some of which are:

- IPCC (IPCC, 2000, 2007, 2013) used IMAGE to elaborate the global mitigation scenarios, which described the relationships between the driving forces and GHG and their evolution during the 21st century in a worldwide level.
- OECD (2008, 2012) used IMAGE to develop the environmental baseline according to the economic projections of the OECD economic model ENV Linkages, and to analyze selected policy intervention cases.
- European Commissions (2005) used IMAGE to explore climate change

abatement targets and regimes in support of EU policy making.

➤ **Other hybrid models**

There are some other hybrid energy models, such as the Energy-Environment-Economy Model for Europe (E3ME) developed by EU (Laboratories: Cambridge econometrics, Ecole Centrale Paris, etc.), the Intermediate Future Forecasting System (IFFS) designed by Department of Energy of US, the Dynamic New Earth 21 (DNE21) model developed by Yokohama National University (Fujii and Yamaji, 1998), the Price Inducing Model of the Energy System (PRIMES) model and the MIDAS model developed by JOULE-program in TEEM group of EU, etc.

The main models discussed in this section are summarized in the following table 2.1, according to their approaches, geographical coverage and time horizon.

**Tab.2.1. Summary of energy-climate models**

<b>Models</b>	<b>Approach</b>	<b>Geographical coverage</b>	<b>Time horizon</b>	<b>References</b>
<b>CGE</b>	Top-down	National	Short-term	(Galiniš and Van Leeuwen, 2000; Kumbaroglu, 2003; Zhang, 2000; Zhang and Baranzini, 2004; Zhang and Folmer, 1998; Zhang, 1998)
<b>GEM-E3</b>	Top-down	Global, regional, and national	Short/medium-term	(Bahn, 2001; Saveyn et al., 2012; Saveyn et al., 2011)
<b>3Es</b>	Top-down	National	Long-term	(Li, 2003)
<b>MACRO</b>	Top-down	National	Long-term	(Chen, 2005; Lim et al., 1998; Papatheodorou, 1990)
<b>EFOM-ENV</b>	Bottom-up	National	Long-term	(Pilavachi et al., 2008; Plinke et al., 1992; Remmers et al., 2004; Sadeghi and Mirshojaeian Hosseini, 2008)
<b>MARKAL</b>	Bottom-up	National and multi-national	Long-term	(Gielen and Changhong, 2001; Larson et al., 2003; Naughten, 2003; Rydén et al., 1993; Sato et al., 1998)
<b>LEAP</b>	Bottom-up	Global, national, and local	Long-term	(Bala, 1997; Bose and Srinivasachary, 1997; Kumar et al., 2003; Shin et al., 2005)
<b>MEDEE</b>	Bottom-up	Regional and national	Long-term	(Lapillonne, 1980; Lapillonne and Chateau, 1981; Messenger, 1981)
<b>AIM</b>	Bottom-up	Asian-Pacific region	Long-term	(Jiang et al., 2000; Kainuma et al., 2000; Matsuoka et al., 1995)
<b>MESSAGE</b>	Bottom-up	Global and regional	Medium/long-term	(Dayo and Adegbulugbe, 1988; Gritsevskiy and Nakicnovi, 2000; Messner et al., 1996)
<b>NEMS</b>	Hybrid	National	Medium-term	(Hadley and Short, 2001; Wilkerson et al., 2013)
<b>POLES</b>	Hybrid	Global (regional- or country-specific study possible)	Long-term	(Criqui and Mima, 2001; Criqui et al., 1999; Russ and Criqui, 2007)
<b>WEM</b>	Hybrid	Global (regional- or country-specific study possible)	Medium/long-term	(IEA, 2011b)
<b>SAGE</b>	Hybrid	Global (regional- or country-specific study possible)	Long-term	(Bhattacharyya and Timilsina, 2010)
<b>IPAC</b>	Hybrid	Global, regional and national	Medium/long-term	(Jiang et al., 2013)
<b>IMAGE</b>	Hybrid	Global	Long-term	(EC, 2005; IPCC, 2000, 2007, 2013; OECD, 2008, 2012)

## 2.2.4 Sub-conclusion of the energy-climate models

In brief: top-down, bottom-up and hybrid models are used to sustain climate policy decisions and evaluate the costs of achieving a certain objective of abatement. These models apply different techniques, including mathematical programming, econometrics and related method of statistical analysis and network analysis (Hoffman and Wood, 1976).

As these models cover normally the whole energy system, they require a huge database, large technology specifications, and extensive computing skills. Meantime, the models considering macro-economic factors generally have production functions that capture substitution possibilities through elasticity of substitution between factors of productions and inputs. Good estimates for these parameters are decisive for a correct evaluation of policy strategies, but normally substitution elasticity for singles country and energy sectors are estimated from aggregate historical data, which do not guarantee that these parameters values can be applicable in the future under the adoption of climate policies (Böhringer, 1998). Indeed the elasticity is not constant in mid-term since it depends on the change of technology or function of production used.

Although both top-down and bottom-up model approaches contribute to assess carbon mitigation options, their results have tended to diverge, with top-down models estimating higher GHG abatement costs (Grubb et al., 1993; IPCC, 2001; Wilson and Swisher, 1993) than bottom-up models. It is generally believed that as top-down models do not contain technological details, they overestimate the economic adjustments and do not take well into account possible technological changes that can be induced by price adjustments associated with energy-related GHG emissions abatement. Thus, top-down models tend to suggest that the efforts to change the energy system away from today's structure would be excessively costly. On the other hand, because bottom-up models ignore the macro-economic feedbacks of different energy or climate policies, they indicate that environmental goals can be reached at an excessive lower cost (Fortes et al., 2009).

These models generally cover the whole energy system, but they turn out to be complex, because of the large numbers of assumptions (e.g. end-use behaviors, the technological specifications, resources allocations, elasticities of substitution, etc.), and the extensive data needed. Besides, these models often require the high level of skills, such as mathematical programming, econometric and related methods of statistical analysis and network analysis.



And the access is required for some models, like the TIMES model, the POLES model, etc. Thus, it is difficult, even for the researchers, to well understand the results of these models. For policy makers, they need clear and consistent information concerning the best strategies to reduce GHG, the real impact of policies in the economy and their effectiveness to reduce emissions. Thus, these divergences between the models' behavior can generate different strategies for carbon reduction, which result in uncertainty for decision-makers and question the model value for assisting the design of policy instruments.

Even though some studies (Grubb et al., 1993; IPCC, 2001; Wilson and Swisher, 1993) have confronted the results of top-down and bottom-up approaches under carbon mitigation options, they frequently focus on the marginal mitigation costs and give little attention to the different sectoral reduction strategies in terms of the carbon equity with different emission scenarios.

Now let's analyze the CO<sub>2</sub> emission scenarios that are often connected with the energy-climate models, but often with different technology pathway assumptions: In the next section 2.3, the CO<sub>2</sub> emission scenarios will be presented by the geographical coverage, world, region, and nation.

## **2.3 CO<sub>2</sub> emission scenarios setting**

At the Conference of Parties (COP) 16 held in Cancún in 2010, Parties to the UN Framework convention on Climate Change (UNFCCC) agreed that future global warming should be limited below 2°C relative to the pre-industrial temperature level. However, the GHG emissions pathways in the future are unpredictable, as the results of human activities, society and technology evolutions.

Emission scenarios describe future emissions level based on assumptions about driving forces such as patterns of economic and population growth, technology development, policies changes, and other factors. Different research projects and institutes have set different emission scenarios, by climate model, by energy-economic model, or by climate objectives, which are referred to top-down and bottom-up methodologies we refer in the previous section. Most studies adopt the bottom-up methodology (IEA, IPCC, etc.), which has the merit of a

clear structure and is easy to identify emissions reduction contributions by each technology. The necessary basic data in the bottom-up methodology is measured by physical but not economic dimension, which implies that they do not integrate macro-economic variables. The studies, such as United Nations Environment Programme (UNEP) and Asian Modeling Exercise (AME), have adopted both the bottom-up model and the top-down model, which includes the economic factors (Li and Qi, 2011).

Many studies (IEA, IPCC, etc.) have proposed global scenarios, since the climate change is a global related issue. The CO<sub>2</sub> emission scenarios can also be categorized by the scale of regions according to specific interest, like regions scenarios (European scenarios, Asian scenarios, etc.), and national scenarios (China scenarios, France scenarios, the United States scenarios, etc.).

In this third section, the emission scenarios categorized by geography scale (world, regions, nations) are presented.

### **2.3.1 The global scenarios**

#### **➤ The IPCC scenarios**

In the fifth Assessment Report (AR5) of IPCC (2014a), there are four CO<sub>2</sub> emissions scenarios categorized according to the Representative Concentration Pathways (RCP) concentrations:

- The stringent mitigation scenario (RCP 2.6);
- Two intermediate scenarios (RCP 4.5 and RCP 6.0);
- And the high GHG emissions scenario (RCP 8.5).

The RCP 2.6 falls in the 430-530 ppm CO<sub>2</sub>eq category, which corresponds to the objective of keeping global warming below 2°C in 2100 above the pre-industrial temperatures. The RCP 4.5 falls in the 530-720 ppm CO<sub>2</sub>eq category, which corresponds to the increase of average climate change less than 3°C in 2100. Finally scenarios without additional efforts to constrain emission ('baseline scenario') lead to pathways ranging between RCP6.0 and RCP 8.5 (IPCC, 2014b).

## ➤ **The IEA scenarios**

In the Energy Technology Perspective (ETP) (IEA, 2014) of IEA, there are three categories of scenarios: 6°C Scenario (6DS), 4°C Scenario (4DS), and 2°C Scenario (2DS).

- The 6DS is set to be the extension of current trends. By 2050, energy use almost doubles (compared with 2009) and total GHG emissions rise even more. In the absence of efforts to stabilize atmospheric concentrations of GHGs, average global temperature rise is projected to be at least 6°C in the long term.
- The 4DS takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency. It serves as the primary benchmark in ETP 2012 when comparisons are made between scenarios. The IEA notes that in many respects, this is already an ambitious scenario that requires significant changes in policy and technologies; it also requires significant additional cuts in emissions in the period after 2050. For example, the CO<sub>2</sub> emissions in China should be limited to 11Gt in 2050, at the same level of that in 2015. The renewable energy should contribute 40% of the emission reductions with respect to the 6°C scenario.
- The 2DS is the focus of ETP, which describes an energy system consistent with an emissions trajectory that recent climate science research indicates of giving an 80% chance of limiting average global temperature increase to 2°C. It sets the target of cutting energy-related CO<sub>2</sub> emissions by more than half in 2050 compared with 2009, and ensuring that they continue to fall thereafter (IEA, 2014).

## ➤ **The UNEP scenarios**

In the UNEP report (2011b), it defines the green economy as an economy that “results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities”. Five scenarios are set according to the impact of different levels and patterns of investment:

- The BAU case replicates history over the period 1970-2009, and assumes no fundamental changes in policy or external conditions going forward to 2050.

- The two green scenarios (G1 and G2) assume increased investments over the period 2010 to 2050.
- And these are contrasted with two respective business-as-usual scenarios (BAU1 and BAU2) in which the same amounts of investments are simulated, but allocated according to existing patterns (UNEP, 2011a).

The details of the investment levels in the scenarios are like following:

- BAU1: investment is increased by 1% of GDP/year compared to BAU, but current trends in resource use and energy consumption, etc. are maintained with no additional investments in renewable energy, different forms of agriculture, and reduced deforestation.
- BAU2: same as BAU1 except that investment is increased by 2% of GDP per year compared to BAU.
- G1: a 1%/year increase in investment that increases resource efficiency and reduces carbon intensity, allocated about equally across the various sectors.
- G2: a 2%/year increase in investment emphasizing green investment in which ‘a higher share of GDP is allocated to energy and the remainder is shared across the remaining sectors (e.g. agriculture, forestry, fishery, waste, transport infrastructure)’ (Victor and Jackson, 2012) .

### ➤ **The LIMITS scenarios**

Low climate IMpact scenarios and the Implications of required Tight emission control Strategies (LIMITS) project conclude twelve partners from Europe, China, India, Japan and the USA. One of the objectives of the project is defining the feasibility of low carbon scenarios and the associated emission reduction pathways according to different assumptions about technology availability, policy regimes, implementation obstacles and regional level of commitment. Seven global integrated assessment modeling frameworks participated in the LIMITS project: AIM-Enduse, GCAM, IMAGE, MESSAGE, TIAM-ECN, REMIND, and WITCH.

The LIMITS has 12 scenarios with the most important features following:

- The long-term climate objective of both 450 and 500 ppm CO<sub>2</sub>-eq, which would yield reasonably high and even chances of achieving 2°C, respectively.
- The level of ambition in 2020, with a more lenient reference policy ('weak') reflecting the unconditional Copenhagen Pledges and a more stringent version ('stringent') based on conditional Copenhagen Pledges.
- The level of international cooperation until 2020 and 2030.
- The burden sharing scheme to be adopted once the international treaty is signed (no sharing, per-capita convergence and equal effort).

### ➤ **The RoSE scenarios**

The RoSE project is coordinated by the Potsdam Institute for Climate Impact Research, and with the participation of 5 leading integrated assessment modeling teams from the EU, U.S. and China.<sup>11</sup>

It produces 6 climate policy scenarios representing different levels of ambition and timing of climate policy action:

- **Baseline:** The baseline represents a no climate-policy case;
- **450ppm:** This corresponds to a 450ppm CO<sub>2</sub> equivalent concentration stabilization target allowing for overshoot and with full when-where-what flexibility of emissions reductions after 2010. It accounts for the radiative forcing of all radiative substances including Non-Kyoto gases and aerosols;
- **550ppm:** This scenario is similar to the previous one, with the exception that the concentration stabilization target is set to 550ppm and that no overshoot is allowed;
- **Weak Policy:** The weak policy scenario describes a situation where world regions take only moderate and uncoordinated action. It follows the lower end of the Copenhagen commitment until 2020 and retains that level of ambition throughout the 21st century;

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<sup>11</sup> The RoSE multi-model ensemble experiment is conducted with the participation of four global integrated assessment models (GCAM, IPAC, REMIND, WITCH) and one regional energy system model (China MARKAL).

- 450ppm in 2020: In this case the weak policy scenario is followed until 2020 and then a 450ppm long term stabilization target, allowing for overshoot, is adopted;
- 450ppm in 2030: This is identical to the previous scenario, only that the 450ppm stabilization target is adopted at 2030.

## 2.3.2 The regional scenarios

### ➤ The AME Scenarios

The Asian Modeling Exercise (AME) is a research project that aims to articulate the role of Asia in mitigating climate change. This study compares results of 23 energy-economic and integrated assessment models, focusing on results for Asian regions.

The AME have three types of scenarios: Reference scenario, CO<sub>2</sub> price path scenarios, and Radiative forcing target scenarios (Akashi et al., 2012):

- Reference scenario is the Basis scenario with no climate policy.
- CO<sub>2</sub> price path scenarios:
  - **CO<sub>2</sub> price \$10 (5% p.a.):** Global CO<sub>2</sub> price path beginning with \$7/t CO<sub>2</sub>-eq in 2013 and increasing at 5%.p.a. CO<sub>2</sub> price in 2020 and 2050 becomes \$10/t CO<sub>2</sub>-eq and \$43/t CO<sub>2</sub>-eq, respectively;
  - **CO<sub>2</sub> price \$30 (5% p.a.):** Global CO<sub>2</sub> price path beginning with \$21/t CO<sub>2</sub>-eq in 2013 and increasing at 5%.p.a. CO<sub>2</sub> price in 2020 and 2050 becomes \$30/t CO<sub>2</sub>-eq and \$130/t CO<sub>2</sub>-eq, respectively;
  - **CO<sub>2</sub> price \$50 (5% p.a.):** Global CO<sub>2</sub> price path beginning with \$36/t CO<sub>2</sub>-eq in 2013 and increasing at 5%.p.a. CO<sub>2</sub> price in 2020 and 2050 becomes \$50/t CO<sub>2</sub>-eq and \$216/t CO<sub>2</sub>-eq, respectively.
- Radiative forcing target scenarios:
  - **3.7 W/m<sup>2</sup> NTE:** Global cost-effective emissions pathway for constraining total radiative forcing at 3.7 W/m<sup>2</sup> in 2100. The radiative forcing target should not be exceeded throughout the entire period;
  - **2.6 W/m<sup>2</sup> OS:** Global cost-effective emissions pathway for constraining total

radiative forcing at 2.6 W/m<sup>2</sup> in 2100. The radiative forcing target should be met in 2100, but can be exceeded during the 21st century.

### ➤ **The JRC scenarios**

The JRC is the European Commission in-house science service, which aims to provide independent scientific and technical advice to the European Commission to support a wide range of EU policies. It develops its JRC-EU-TIMES model with two CO<sub>2</sub> emission scenarios: the reference scenario and the decarbonization scenario.

It has two scenarios, the reference scenario and the decarbonized scenario (Peteves et al., 2013):

- The reference scenario, which is the baseline scenario, is based on the implemented policies;
- The decarbonized scenario assumes a total reduction of CO<sub>2</sub> emissions by 85% with respect to 1990, in the spirit of the EU Roadmap for moving to a Low Carbon Economy.

Now examples of national scenarios for France, China and the United States, the three countries that will be studied in the next chapters 3 and 4.

## **2.3.3 The national scenarios**

### ➤ **The ANCRE scenarios**

L'Alliance Nationale de Coordination de la Recherche pour l'Energie (ANCRE) is a French alliance founded by CEA, CNRS and IFP Energies Nouvelles (Alazard-Toux et al., 2014).

It defines 3 scenarios for France under the policy “facteur 4” to 2050, e.g. ‘Sobriété renforcée’ (SOB) scenario, ‘Décarbonisation par l'électricité’ (ELE) scenario, and ‘Vecteurs diversifiés’ (DIV) scenario:

- The SOB scenario relies on a major evolution of individual behavior to reduce

the energy demand, to improve the energy efficiency and the renewable energy development, e.g. it assumes an important habitat renovation (650 000 housing/yr against the actual level at 125 000);

- The ELE scenario is based on the combination of important efforts on the energy efficiency and increasing different uses of the carbon-free electricity, e.g. it plans to have 45% of the electric mobility in 2050;
- The DIV scenario relies on energy efficiency and focus on the diversification of the energy sources, with an important contribution from the biomass, the waste heat recovery (including that of nuclear reactors) and an important role of intelligent energy systems.

### ➤ **The ERI scenarios**

The ERI of National Development and Reform Commission of China is a national research organization conducting comprehensive studies on China's energy issues.

It has three scenarios, the BAU scenario, the Low Carbon (LC) scenario, and the Enhanced Low Carbon (ELC) scenario (ERI, 2010):

- In the BAU scenario, the economy is the main driving force, with high consumption pattern, concern on environmental protection and technology progress.
- The LC scenario is more driven by sustainable development, with combined measure, such as, new energy technology adoption, energy saving and enhanced technology innovation and development, etc.
- The ELC scenario is driven by the global objective of emission reduction with the efforts of the entire world. More investments in the low carbon technology will be made and the advanced technologies, such as CCS, will be adopted.

### ➤ **The AEO2014 scenarios**

The AEO by U.S. Energy Information Administration (EIA) (2014) present long-term annual projections of energy supply, demand, and prices focused on the United States based



on the results from EIA's NEMS. Three scenarios (apart from the Reference scenario) are developed for the energy-related CO<sub>2</sub> emissions between 2000 and 2040:

- Reference scenario: the business-as-usual trend estimate, given known technology and technological and demographic trends. Real GDP grows at an average annual rate of 2.4% from 2012 to 2040. Crude oil prices rise to about \$141/barrel (2012 dollars) in 2040.
- GHG10 scenario: Applies a price for CO<sub>2</sub> emissions throughout the economy, starting at \$10 per metric ton CO<sub>2</sub> emissions in 2015 and rising by 5% per year through 2040.
- GHG25 scenario: Applies a price for CO<sub>2</sub> emissions throughout the economy, starting at \$25 per metric ton CO<sub>2</sub> emissions in 2015 and rising by 5% per year through 2040.
- GHG10 and Low Gas Prices scenario: combines with Low natural gas prices than in the Reference case.

All the CO<sub>2</sub> scenarios presented above are summarized in the table 2.2, covering the institutes, methodologies, models types, geographical scales and its target year.

**Tab.2.2. Summary of CO<sub>2</sub> emission scenarios setting**

<b>Study</b>	<b>Methodology</b>	<b>Model</b>	<b>Scale</b>	<b>Target year</b>	<b>Scenarios</b>
<b>IPCC</b>	Bottom-up	IAMGE	World	2100	RCP8.5, RCP6.0, RCP4.5, RCP2.6
<b>IEA</b>	Bottom-up	ETP	World	2050	6DS, 4DS, 2DS
<b>UNEP</b>	Top-down, bottom-up	Threshold 21	World	2050	BAU, BAU1, BAU2, G1, G2
<b>LIMITS</b>	Bottom-up	Multi models (e.g. GCAM, MESSAGE, AIM-Enduse, etc.)	World	2020, 2030, 2100	Baseline, 450 CO <sub>2</sub> e, 500 CO <sub>2</sub> e
<b>RoSE</b>	Bottom-up	Multi models (e.g. GCAM, WITCH, IPAC, etc.)	World	2100	Baseline, 450 CO <sub>2</sub> e, 550 CO <sub>2</sub> e, Weak Policy, Baseline, 450 CO <sub>2</sub> e after 2020, 450 CO <sub>2</sub> e after 2030
<b>AME</b>	Top-down and Bottom-up	AIM/Enduse, AIM/Impact	Asia, rest of the world	2050	Reference scenario, CO <sub>2</sub> price path scenarios, Radiative forcing target scenarios
<b>JRC</b>	Bottom-up	JRC-EU-TIMES	EU27	2050	Reference scenario, decarbonized scenario
<b>ANCRE</b>	Bottom-up		France	2050	SOB, ELE, DIV
<b>ERI</b>	Top-down, Bottom-up	IPAC-SGM, IPAC-AIM, IPAC-Emission/Technology	China	2050	BAU, LC, ELC
<b>EIA</b>	hybrid	NEMS	The US	2040	Reference, GHG10, GHG25, GHG10 and Low Gas Prices

### **2.3.4 Sub-conclusion of the CO<sub>2</sub> emission scenarios**

In the section 2.3, we have summarized different scenarios of CO<sub>2</sub> emissions generated from different models and institutes. These scenarios imply the objectives of reducing CO<sub>2</sub> emissions, on the worldwide level, regional level, or national level. They are principally three categories of scenarios: 1) The baseline scenario, serves as the reference scenarios; 2) The target-oriented scenario, such as 2DS scenario; and 3) The model-generated scenarios with certain economy or technology assumptions, such as G2 scenario. However, the models and scenarios are principally set under the consideration of optimal costs, and they do not involve the carbon equity factor in choosing the technology roadmaps, which is an important issue in the international negotiations on the climate change problem.

As agreed in the COP16 in Cancún, the increase of the earth's average temperature should be inferior to 2°C with respect to the pre-industry level, which means to stabilize the concentration of GHG emissions under 450ppm CO<sub>2</sub>eq. However, 66% of the carbon budget compatible with the 2°C goal has already been used up to 2010. The remaining amount for GHG is 1000Gt CO<sub>2</sub>. In 2010, of the 49Gt CO<sub>2</sub>eq anthropogenic GHG emissions, 65% come are CO<sub>2</sub> emissions from the fossil fuel combustion. According to the AR5 of IPCC, the global CO<sub>2</sub> emissions from fuel combustions should be reduced to 10Gt in 2050 in order to limit the increase of global temperature under 2°C.

Obviously, all member countries try to have more emission spaces in the limited global CO<sub>2</sub> emission budget, as the CO<sub>2</sub> emissions are often the sub-product of the economy development. Thus, the carbon equity will certainly be involved in the CO<sub>2</sub> emission budget allocation. There are different CO<sub>2</sub> emission budget allocation methods, corresponding to the benefits of different types of countries. In the next section, we will present the CO<sub>2</sub> emission budget allocation approaches, and the indices in measuring the CO<sub>2</sub> inequalities.

## 2.4 Carbon equity issues and its indices

Stabilization of GHG emissions concentrations, as mandated by the UNFCCC, implies establishing limits to the level of global emissions and distributing this level among different countries. There are strong differences in the level of emissions caused by the inhabitants of different parts of the world. The inequality of per capita CO<sub>2</sub> emissions among countries shows different responsibilities in the generation of GHG and the contribution to climate change. Thus, the emission distribution has become an important issue when dealing with the negotiation and agreement of policies for global climate change. The climate change policy involves establishing limits to the level of global emissions and distributing this level among the different countries or regions. As noted above, these limitations might involve economic sacrifices, as emissions are an undesired sub-product of economic activity.

The level of action that each country would need to undertake should be considered to achieve the climate objective in the negotiations. Several studies in the scientific literature aim at supporting this process by calculating possible emissions reduction targets for countries or regions based on so-called ‘effort sharing’ or ‘burden sharing’ approaches (Gupta and Bhandari, 1999; Höhne et al., 2013; Raupach et al., 2014; Ringius et al., 2002; Yedla and Garg, 2014).

Most of these studies first define a global level of GHG emissions in a certain year or period, one that is consistent with meeting a long-term climate objective (e.g. 400–450 ppm CO<sub>2</sub>eq, as used in many recent studies), then apply rules or criteria to allocate efforts to countries or regions with the aim of meeting the global emissions level.

Some studies also provide a distribution of emissions if global emissions were reduced to the same level in the most cost-efficient manner, i.e. where the mitigation costs are lowest. The initial allocation based on effort sharing and a cost-effective distribution is not normally the same for most countries (Höhne et al., 2013).

The emission allocation approaches across countries provide different criteria (i.e.

the historical responsibility, per capita responsibility, per GDP responsibility, etc.) in distributing the CO<sub>2</sub> emission budget. The most used emission allocation approaches will be introduced in this section. And then the inequality indices, which serve as the tool in measuring the carbon inequality we will present: namely Gini and Theil indices.

## **2.4.1 Emission allocation approaches**

Large number of effort-sharing approaches can be categorized using equity principles, such as general concepts of distributive justice or fairness (Rose et al., 1998). Different categorizations of these principles can be found in the literature (Aldy et al., 2003; Ringius et al., 2002; Rose et al., 1998).

For instance, Den Elzen and Lucas (2003) discussed ten emission allocation models based on four equity principles, which are egalitarian, sovereignty, responsibility, and capability:

- **Responsibility:** based on the historical contribution to the global GHG emissions. It comes from the Article 3 of UNFCCC which states that countries should take action on the basis of common but differentiated responsibilities and respective capabilities.
- **Capability:** it indicates the basic needs principle which is also mentioned as the “right to development”. It also comes from the Articles 3 of UNFCCC.
- **Equality:** it is relevant to the equal rights per person to pollute or to be protected from pollution.
- **Sovereignty:** all countries have the right to use the atmosphere, and current emissions constitute a “status quo right”.

The main divide in the equity debate is between developed countries, whose GHG emissions are the major cause of climate change and who are often better equipped to deal with it; and developing countries, many of whose emission levels are increasing,

and who may have more opportunities, albeit fewer resources, to make their economies less greenhouse-intensive (Heyward, 2007).

Basically, there are three main methods to distribute the “burden sharing” of the carbon budget in terms of equity, 1) the equal per capita emission rights approach, 2) the equal per capita cumulative emission approach, and 3) the grandfathering approach:

- The equal per capita emission rights approach allocates emission rights to countries in proportion to their population, but only for the remaining portion of the global carbon budget.
- The equal per capita cumulative emission approach seeks equality in all the emission period, which means the sum of per capita emissions from the industrial period to 2050 (or 2100) across countries are the same level. This approach is more adopted by the developing countries, based on the principle of historical responsibility.
- The grandfathering approach is applied in proposes the emission rights on existing patterns (e.g. The Kyoto Protocol requires the parties countries to reduce their emissions relative to their levels in 1990). This approach permits the countries that emitted more in the past are entitled to emit more in the future than the countries which emitted less in the past.

The harmful effects of global climate change, degrees of contribution to it, and costs of its mitigation vary immensely between nations (Heyward, 2007). There is no definitive emission allocation measure in the international negotiation, as the different countries have their different perspectives and benefits. However, the level of carbon inequality across countries can be measured with inequality indices.

There are generally two measures in explaining the carbon equity, one is per capita emission, and the other is emission per GDP (emission intensity). The former measure represents the human right in emitting from different countries, the latter shows the emission right is related to the economy development. Most of the carbon inequality works use the per capita emission to represent the carbon equity.

In the following section, we will present the most used indices in measuring the carbon inequality.

## 2.4.2 Carbon equity indices

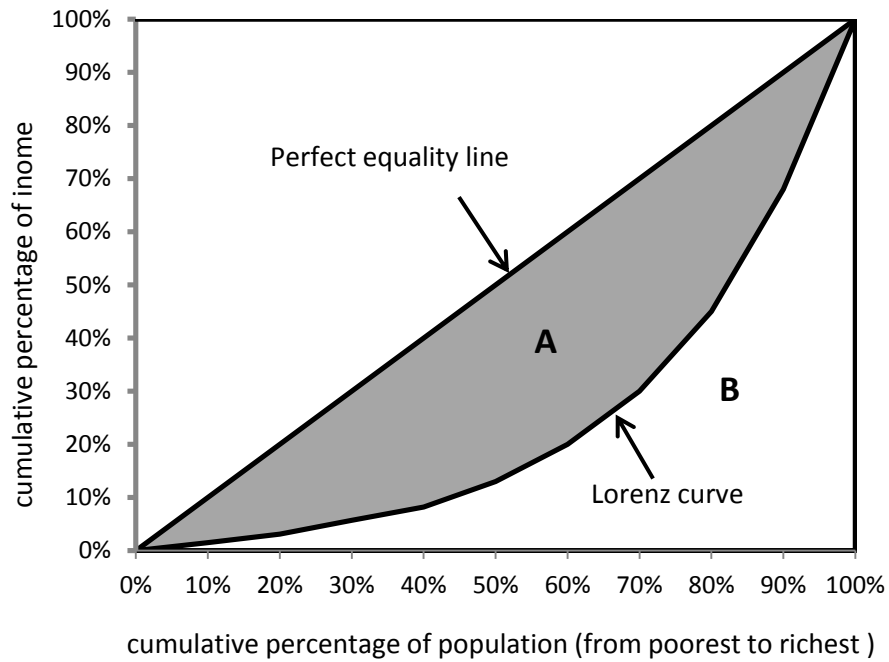
Besides the emission allocation across countries, the ways to evaluate the carbon inequality is also an important subject in the carbon equity issue. In the literatures on the climate change, there have been several attempts to use the tools of income distributive analysis to measure inequality in CO<sub>2</sub> emissions and CO<sub>2</sub> intensities across countries and its development over time (Groot, 2009). Gini coefficient and Theil index are two most used inequality index in the carbon inequality study.

### ➤ Gini index

The Gini index is calculated from the Lorenz curve, which was developed by Corrado Gini (1912) and applied by Dalton (1920) to study the problem of income distribution. The Gini index was originally a graphical representation of the cumulative proportion of individuals' income, mapped against the corresponding cumulative proportion of these individuals (Munnich Vass et al., 2013). And from then on, it is widely used in many countries to evaluate the level of income equality. The United Nations also employs the Gini index as the reference in representing the gap between the wealthy and the poor (Fang et al., 2013).

Conventionally, the Lorenz curve shows the distribution of income according to the percentage of households, where households are ranked by level of income. Figure 2.1 shows the definition of Gini coefficient. The x-axis is the cumulative percentage of population ranked from the poorest to the richest. The y-axis is the cumulative percentage of income. Thus, the 45° line represents the perfect income equality. And the surface between the equality line and the Lorenz curve compared to the surface between the equality line and the horizon axis is defined as the Gini coefficient, in the interval between 0 and 1.

The United Nations suggests Gini coefficient to reflect the gap between the wealthy and the poor. Below 0.2 is defined to be perfect equality, and 0.4 is generally considered as the “picket line” of the income disparity.



**Fig.2.1. Gini coefficient and carbon Lorenz curve**

Applying the Lorenz curve in the context of CO<sub>2</sub> emissions means to replace households by countries and the ranking by income replaced by ranking by CO<sub>2</sub> emissions per capita across countries (Groot, 2009). Thus the vertical axis is the cumulative share of CO<sub>2</sub> emissions, and the horizontal axis is a set of countries ranked by the GDP per capita. The 45° line represents the perfect equality between the CO<sub>2</sub> emissions per capita and the GDP per capita, which means the per capita CO<sub>2</sub> emissions are equal for all level of per capita GDP according to different countries. And the curve is the Lorenz curve of CO<sub>2</sub> emissions per capita, which presents the actual disparities of per capita CO<sub>2</sub> emissions according to different level of per capita GDP. If we note the surface between the equality line and the Lorenz curve is A, and the surface between the Lorenz curve and the horizon axis is B. Then, the Gini index can be presented graphically as  $\frac{A}{A+B}$  according to the figure 2.1.

The formula of Gini index is proposed as following (Dorfman, 1979):

$$G = 1 - 2 \int_0^1 L(u)du \quad (1)$$

where  $L(u)$  is the function of Lorenz curve, with  $u$  the distribution of CO<sub>2</sub>



emissions ranked by the level of income.

Heil and Wodon (1997) used the Gini index to measure the inequality of emission across countries from 1960 to 1990. In this article, they calculated the evolution of per capita emission inequality across groups of countries, where countries are divided into four groups according to level of income. The results show that the between groups inequality component is far more important than the within group inequality component by applying the Gini index. Heil and Wodon (2000) have also employed this methodology to conduct a study of perspective inequality to 2100, by considering the relative scenarios and Kyoto Protocol and other reduction measures.

The Gini coefficient is widely used as a measure to evaluate the inequality, but it only defines the level of inequality. It is difficult to decompose the inequality into driving forces, and difficult to be depicted into mathematical equations.

Another weakness of Gini index is that it is incapable of differentiating different kinds of inequalities. Lorenz curves may intersect, reflecting differing patterns of income distribution, but nevertheless resulting in very similar Gini coefficient values (De Maio, 2007).

Similarly with Gini index, there is another comparative index named pseudo-Gini index developed by Yitzhaki and Lerman (1991). Different from the Gini index in which the distribution of emissions are ranked in the distribution of income, the pseudo-Gini index is computed through the concentration curves of emissions-curves that show the percentage of emissions that concentrate different shares of population, ordered in increasing value of per capita income. Therefore, the concentration index, pseudo-Gini of emissions, shows the inequality in emissions between the populations in rich and poor countries. That is to say, it shows to what degree the inhabitants of rich countries emit more than those of poor countries (Padilla and Serrano, 2006). The pseudo-Gini is often used as a comparative index along with Gini index.

### ➤ **Theil index**

The Theil index (Theil, 1967) is set to calculate the per capita CO<sub>2</sub> emissions

across the world and regions. The Theil equation is presented as following:

$$T(c, p) = \sum_i p_i * \ln\left(\frac{\bar{c}}{c_i}\right) \quad (2)$$

where  $p_i$  is the share of country  $i$  in the total population,  $c_i$  is the per capita CO<sub>2</sub> emissions in country  $i$ , and  $\bar{c}$  is the world average per capita CO<sub>2</sub> emissions.

Different from Gini coefficient, Theil index can be easily presented in the equation, and thus easily to be decomposed into driving forces (e.g. into Kaya factors: (Duro and Padilla, 2006). However, unlike the Gini coefficient, Theil index do not have a standard criterion to evaluate the level of inequality. But it is obvious that the smaller the absolute value of Theil index is, the smaller the inequality is.

Duro and Padilla (2006) applied the decomposable Theil index of inequality to emissions. In this work, they proposed to study the driving forces behind CO<sub>2</sub> emissions, such as economic and demographic development, etc. They employed an analytic tool that is conventionally used for exploring the main driving forces behind this pollutant behavior is the Kaya (1989) identity<sup>12</sup>. According to this identity, per capita CO<sub>2</sub> emissions are decomposed into the product of three basic factors, which are carbon intensity of energy, energy intensity and income level. The results show convincingly that global inequality in per capita emissions is largely due to inequalities in per capita income across countries, and the between-group inequality component, which is the more important than the within-group inequality, is also largely explained by the income factor.

Padilla and Serrano (2006) studied the relationship between CO<sub>2</sub> emissions and GDP, by using the non-parametric estimation technique. The result explained the Environment Kuznet Curve, showing that the income inequality across countries has been followed by an important inequality in the distribution of emissions. Later, Padilla and Duro (2013) analyzed the inequality of per capita CO<sub>2</sub> emissions in the European Union with Theil index for the period 1990-2009, by decomposing the inequality into Kaya factors within groups and between groups.

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<sup>12</sup> Kaya identity presents the CO<sub>2</sub> emission as the product of population, average income (GDP/Population), energy intensity (Energy consumption/GDP), and carbon intensity (CO<sub>2</sub> emission/Energy consumption).

With respect to inequality of energy intensity, Sun (2002) have analyzed the inequalities of energy intensity using the mean deviation method. In his work, he indicated that the inequality of energy intensity in OECD countries and their groups had decreased, except the Pacific group, between 1971 and 1998 by dividing the OECD countries into four groups. But Alcantara and Duro (2004) argued that the weighted mean deviation method, which is the Theil index, should be more reasonable than the unweighted mean deviation method under the consideration of the sizes of countries. Alcantara and Duro (2010) analyzed the inequality of energy intensity levels between OECD countries by decomposing the per capita energy consumption into income and energy intensity. The results show that although differences in affluence are the most significant factor in explaining inequality in energy consumption per capita, the inequality in energy intensity levels plays a prominent role in reducing the inequality in per capita energy consumption. Duro and Padilla (2010) analyzed the role of the energy transformation index and of final energy consumption per GDP unit in the disparities in energy intensity across countries by using the Theil index. The results present that inequality of energy intensity is largely due to the inequality of final energy consumption per GDP, for both intra-groups and inter-groups.

### ➤ **Other carbon inequality indices**

Besides the Gini index and Theil index, there are other inequality indices used in the carbon inequality issues, but always served as the supplementary methods, such as coefficient of Variation (CV), Atkinson index and Kakwani index.

The CV is calculated by dividing the standard deviation of the income distribution by its mean. Its formula is shown in the table 2.3. The more equal the income distribution is, the smaller the CV index is. This index is the simplest inequality measure. It is readily intelligible, but it is sensitive to outliers, which means that it may be exceedingly influenced by anomalously low or high income values (Clarke-Sather et al., 2011).

Atkinson index (1970) is a commonly used economic measure of inequality, which is based on the utility function. Its formula is shown in the table 2.3. It allows varying sensitivity to inequalities in different parts of the income distribution. The Atkinson index incorporates a sensitivity parameter  $\epsilon$ , which can range from 0 (meaning that the researcher is indifferent about the nature of the income distribution), to infinity (where the researcher is concerned only with the income position of the very lowest income group). Hedenus and Azar (2005) measure emission inequality across countries by the absolute and relative gap between the top and bottom quintile per capita carbon emitters and by the Atkinson index over the interval 1961-1999.

The Kakwani index (De Maio, 2007) builds from the Gini framework, with its formula shown in the table 2.3. It can be represented as the difference between the Pseudo-Gini index of CO<sub>2</sub> emissions and the Gini index of income. The Kakwani index computes the extent to which the inequality in the distribution of emissions between rich and poor countries is greater than the inequality in the distribution of income. In other words, the Kakwani index computed the level of “progressivity” of the distribution of emissions. Thus a negative number indicates that CO<sub>2</sub> emissions are less concentrated (more equally distributed) than income, while a positive number indicates that CO<sub>2</sub> emissions are more concentrated (less equally distributed) than income (Clarke-Sather et al., 2011).

These indices, along with Gini and Theil index, are often employed in the same study for conducting a comprehensive comparison. For instance, Padilla and Serrano (2006) revealed that the inequality has diminished between the rich and poor countries, with Gini index, Kakwani index and Theil index. Then Clarke-Sather et al. (2011) compared the carbon inequality on a sub-national level in China between 1997 and 2007 using several measures: Gini index, Theil index, Kakwani index and CV.

The formulas of the inequality indices presented in this section are summarized in the following table 2.3.

**Tab.2.3. Summary of carbon inequality indices**

<b>Index</b>	<b>Equation</b>	<b>Assumptions</b>	<b>References</b>
<b>Atkinson</b>	$1 - \frac{1}{\mu} \left( \frac{1}{N} \sum_{i=1}^N y_i^{1-\varepsilon} \right)^{1/(1-\varepsilon)}$ for $0 \leq \varepsilon \neq 1$ $1 - \frac{1}{\mu} \left( \prod_{i=1}^N y_i \right)^{1/N}$ for $\varepsilon = 1$	Where $\mu$ is the mean income, $y_i$ is individual income, $\varepsilon$ is the inequality aversion parameter.	(Hedenus and Azar, 2005)
<b>CV</b>	$\frac{\sqrt{\sum_{i=1}^N (y_i - \bar{y})^2 / N}}{\bar{y}}$	Where $y_i$ is the per capita CO <sub>2</sub> emissions of individual $i$ . $N$ is the number of individuals. $\bar{y}$ is the mean per capita CO <sub>2</sub> emissions.	(Clarke-Sather et al., 2011)
<b>Gini</b>	$1 - 2 \int_0^1 L(u) du$	Where $L(u)$ is the Lorenz curve function, with $u$ the distribution of the CO <sub>2</sub> emissions ranked by the income level.	(Clarke-Sather et al., 2011; Groot, 2009; Grunewald et al., 2014; Heil and Wodon, 2000; Padilla and Serrano, 2006)
<b>Kakwani</b>	$pGini - G_i$	Where $pGini$ is the pseudo-Gini index of CO <sub>2</sub> emissions, $G_i$ is the Gini index for income.	(Clarke-Sather et al., 2011; Padilla and Serrano, 2006)
<b>Pseudo-Gini</b>	$1 - 2 \int_0^1 L(v) dv$	Where $L(v)$ is the Lorenz curve function, with $v$ the distribution of the CO <sub>2</sub> emissions ranked by the population share.	(Clarke-Sather et al., 2011; Groot, 2009; Padilla and Serrano, 2006)
<b>Theil</b>	$\sum_i p_i * \ln\left(\frac{\bar{c}}{c_i}\right)$	Where $p_i$ is the share of country $i$ in the total population, $c_i$ is the per capita CO <sub>2</sub> emissions in country $i$ , and $\bar{c}$ is the world average per capita CO <sub>2</sub> emissions.	(Clarke-Sather et al., 2011; Duro and Padilla, 2006; Padilla and Duro, 2013; Padilla and Serrano, 2006)

### **2.4.3 Sub-conclusion of the carbon equity**

In this section, we have presented the carbon budget allocation approaches and the carbon inequality indices. The carbon equity issue is often discussed in the debate between developed and developing countries and in the international negotiations (Heyward, 2007; Roberts, 2001; Yedla and Garg, 2014). The studies of the carbon equity generally focus on the carbon budget allocation by applying different equity principles. As for the measurement of carbon inequality, most carbon equity researches are carried on the study of driving forces of carbon inequality and the relationship between carbon inequality and income inequality (Duro and Padilla, 2006; Padilla and Serrano, 2006).

We have seen the equity issues are rarely - in the way we will do it in Chapter 4, i.e. with the use of explicit carbon inequality index - integrated in the energy-environmental models and in the setting of CO<sub>2</sub> emissions. Besides, carbon inequality is generally discussed on the international, regional, or sub-national level, rarely discussed on the energy sector level. Thus the carbon equity is rarely involved in defining the technology roadmaps.

## **2.5 Conclusion**

In this chapter, we have reviewed the literatures on the energy-climate models, the CO<sub>2</sub> emission scenarios, and the carbon equity studies. Different models have been presented on the subject of the technology roadmaps related to the climate objective, categorized by the approaches of top-down (e.g. CGE model), bottom-up (e.g. MARKAL model), and hybrid (e.g. POLES model). These models are now well developed, covering the whole energy system with detailed technologies specification. But new and future technologies are difficult to be added in these models (e.g. CCS,

storage technologies, and other electrifications). Besides, they require generally huge database and high a level of mathematical programming skills.

Besides some CO<sub>2</sub> emissions scenarios are integrated with these models: We have shown the CO<sub>2</sub> emissions scenarios and the models help to decide the technology roadmaps in minimizing the total costs. However, they rarely consider the carbon equity issue in the modeling.

Next, the carbon equity is a very important issue in the climate change negotiations: We have presented the CO<sub>2</sub> emission budget allocation principles and the most important allocation approaches. International negotiations fail when they approach the inequality of per capita emissions: the debates oppose developing and developed countries, as it represents the different capacities and responsibilities for different countries. The most famous carbon inequality indices, Gini and Theil index, were introduced in the end of this chapter. The two indices are most used in the current carbon inequality studies (Clarke-Sather et al., 2011; Padilla and Serrano, 2006): each method have its own advantages and defaults (i.e., Gini index is easy to understand, but as a graphic index, its mathematical formula is not clear enough to be employed in the optimization; however, the Theil index has a simple formula but there is no standards in the evaluation, thus it is commonly used in a relative way for the comparison); the use or the integration of one index will depend on the specifications and variables of the energy model. In the next chapters of the thesis, we will propose a way to add these indices of carbon inequality into the modeling of the technology roadmaps.

As the result of the complexity of the existing models, we will set up a more simple and flexible model for the policy makers in the next chapter. A model covers the main energy sectors. Our model should also be possible to be customized, where the new technologies can be easily added, and the technology roadmaps can be chosen according to different criteria. Here the objectives are:

- Chapter 3: Our model we entitle “Sectoral Emission Model” meeting these requirements, will provide different technology roadmaps.
- Chapter 4: Then the carbon inequality will be integrated in the model which will impact the technology roadmaps.

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# Chapter 3

## **The Sectoral Emission Model: a Flexible Energy Transition Modeling for China, France and the US, from 2010 to 2050**

### **3.1 Introduction**

In 2010, the global temperature had increased by 0.85°C compared to the pre-industry level according to the Fifth assessment report (AR5) of IPCC (IPCC, 2013). With the continuation of this growth rate, the global mean surface temperature will increase by 3.7°C to 4.8°C in the end of this century. However, an increase of 2°C of the earth's average temperature above pre-industrial levels is envisaged as the maximum level for now, which has been agreed by negotiators and politicians in the COP16 in Cancún 2010. Above the increase of 2°C, the degree of additional risk would increase dramatically due to the climate change according to experts (IPCC, 2014a).

Since the global warming is highly resulted by the anthropogenic GHG emissions, CO<sub>2</sub> emissions, which account for about two thirds of GHG emissions, are the primary sources to be reduced in the future. In order to achieve the objective of 2°C, the global CO<sub>2</sub> emissions need to be cut down to half of the level in 1990 at approximately 10Gt in 2050, which means a reduction of 67% compared to the 2010 level (IPCC, 2014a).

Actually, the global CO<sub>2</sub> emissions from fuel combustion increased from 14 065 million tonnes (mt) to 30 276 million tonnes, from 1971 to 2010. Meantime, in the same period, the world population has increased by 80% and for the world GDP, by 260%. In the future, the worldwide economic development will undoubtedly require increasing energy production. The rise in energy demand by some industrial areas and countries will inevitably put pressure on natural resources and climate. What exactly will happen if we continue the current international and national efforts? And what should we do to stay below the famous target of 2°C?

It is difficult to exactly forecast future energy use and CO<sub>2</sub> emissions, as they depend on many exogenous and unpredictable factors, such as energy prices, energy policies, demographic changes, economic growth, international economic health, and technical change. Despite of these numerous uncertainties, academic works on energy projections have no choice but to rely on historical data. Such projections can obviously be often inaccurate if they do not include information on future changes. In this context, various qualitative energy scenarios are used in the projection modeling: for example, several associations and institutes (e.g. IPCC, IEA, etc.) have worked in developing such contrasting scenarios for CO<sub>2</sub> emissions, growth, behaviors of economic agents, etc. (IEA, 2014; IPCC, 2014a), in order to identify the main driving forces of change. Therefore macroeconomic modeling of energy and climate is now considered more often in this direction.

But several families of applied models still co-exist with strong differences in terms of decompositions (sectorial, regional, fiscal, etc.), theories used (endogenous or exogenous growth, market's structures, etc.) and long or mid-term perspectives (Chen, 2005; Klaassen and Riahi, 2007; Saveyn et al., 2012) as we have shown it in the previous chapter (Chapter 2). Mechanisms and assumptions of the existing applied economic models can often be very opposed which makes it very difficult to compare the results and well understand the numerous differences in predictions (Boulanger and Bréchet, 2005). Each of the existing models has its own strengths and weaknesses. Eventhough the complex model, such as MARKAL model, AIM model, NEMS model, etc., make a full coverage of the energy sectors and energy flues, but they also requires large amount of exogenous inputs and complex structures with limited access.

Different from these existing models, we propose a less complex (less data required, simple framework, etc.) but complementary approach: our Sectoral Emission Model with three main energy sectors (power, transport, and the others, including residence and industry: which account for about more than 80% of the carbon emissions) by studying the main energy related technologies: energy mix in power generation, the Carbon Capture and Storage (CCS), electric vehicles and energy efficiency.

In our work, we apply the model for three types of country that may be considered to represent a number of other similar countries in the world:

- China (CN): a fast-emerging economy that requires increasing energy consumption, and the largest emitter of CO<sub>2</sub>;
- France (FR): a well-developed economy with relatively low CO<sub>2</sub> emissions;
- The United States (US): the largest economy and a major source of CO<sub>2</sub> emissions.

Here in this work, different from the scenarios generated by the models presented in Chapter 2, we adopt several target-oriented CO<sub>2</sub> emissions scenarios, such as 2°C scenario, in order to depict the energy transition pathways. Our model allows calculating the future emissions of CO<sub>2</sub> according to:

- Business-as-Usual scenarios of China, France, and the United States; the dynamic of the targets announced by the three governments;
- The dynamic of the emissions recommended by the IPCC (2°C and 3°C scenarios with two allocation approaches: grandfathering and equal emission convergence).

By so doing, we can easily answer the first question: are the measures announced or recommended of CO<sub>2</sub> mitigations achievable regarding the particular situation of the country and possible future changes?

For robust predictions, two methodologies are applied. The first is the Stochastic Impacts by Regression on Population Affluence and Technology (STIRPAT) model. It helps us to simulate the Business-as-Usual scenarios for CO<sub>2</sub> emissions by country.

STRIPAT is preferred for IPAT (which assumes that the environment Impact is the results of Population, Affluence and Technology) since it models statistically the non-proportionate impacts of variables on the emissions: we refer to the articles of (Dietz and Rosa, 1994, 1997; Lin et al., 2009; Martinez-Zarzoso and Maruotti, 2011; Meng et al., 2012; Squalli, 2010; Wei, 2011; York et al., 2003).

Second, for future electricity production and the CO<sub>2</sub> emission intensity of production of the different fuels, we use the Support Vector Regressions (SVR) method dedicated to non-linear regressions (Cortes and Vapnik, 1995) to model them. The method has proved to be relevant for electricity load forecasting (Hong, 2010; Wang et al., 2009) based on a small database.

All possible solutions for the technology pathways can be generated with our Sectoral Emission Model, offering the policy makers choices of technology transition solutions according to their different criteria. Besides the solution pool of the technology roadmaps, here we provide two more: with “balanced technology development” across sectors<sup>13</sup>; and with “least changed energy mix”<sup>14</sup>. In addition, the sensitivity of the model with parameters under these two roadmaps is tested.

The results of the model show:

- First, the governmental targets in France and the United States are very strict: That is to say, these two countries have given stronger objectives as would have been their goals, if all countries had undifferentiated goals to stabilize the climate (i.e. they all had the same reductions of GHG). Governmental targets in France and in the United States then require all sectors make large efforts in reducing CO<sub>2</sub> emissions. In France, two thirds of emission reductions are expected to be contributed by the transport sector. 80% of vehicles should be changed to electric vehicles for reaching its governmental target. Meanwhile, the energy efficiency

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<sup>13</sup> “balanced technology development” across sectors refers to the same proportion advanced by each technology in reducing CO<sub>2</sub> emissions.

<sup>14</sup> “least changed energy mix” refers to minimize the difference between the energy mix in the power sector in 2050 and that in 2010, under the consideration of exploitation at maximum their own sources for each country.

should also be improved by 80%. As the power sector contributes little to the CO<sub>2</sub> emission, CCS is not a necessary option for France.

- Second, the governmental target in China is more tolerant (i.e. less than if all countries had the same reductions of GHG), where the advancement of technologies is less demanded than in France or in the United States. In China, half of the emission reductions are expected to be contributed by the power sector, as the power sector accounts for half the the emissions in 2010. In the 2°C grandfathering scenario and 2°C equal emission scenario, China is obliged to decarbonize at maximum all the sectors in 2050. While for the governmental target (which is more tolerant), 60% of vehicles should be replaced by electric vehicles, energy efficiency should be improved by 60%, and coal utilization should be reduced by 60%.
- Third, if the energy mix is expected to be kept quite unchanged in China and in the United States, the CCS should be implemented to all power plants to reach the goals. Since CCS technology is estimated to absorb about 90% of the CO<sub>2</sub> emissions (IPCC, 2005). However, this technology is not yet largely applied in the power sector and industry considering of security and high costs.
- Last, the tests of sensitivities of parameters in the model for different technology roadmaps in different countries show that the electricity output and the emission intensity of production are the two parameters with the most important sensitivity on CO<sub>2</sub> emissions. Thus, improving the energy efficiency of coal combustion and of electricity production will play an important role in the emission reductions.

The remainder of this chapter is organized as follows:

- Section 2 introduces the structure of our Sectoral Emission Model, which is made in response to the criteria which aim to set up a flexible and simple sectoral model as in the previous chapter.
- Section 3 presents the scenarios for CO<sub>2</sub> emission and population, GDP

data for China, France and the United States.

- Section 4 then explain the results obtained from the model according to different countries.
- Conclusions are drawn in the section 5.

## **3.2 The Sectoral Emission Modeling**

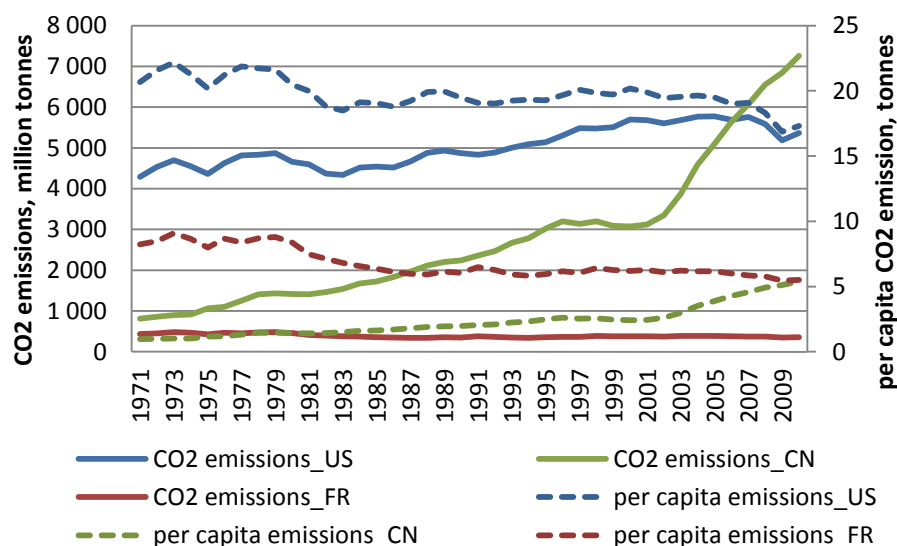
In the first sub-section, the modeling background will be introduced. Then, the modeling framework will be presented in the second sub-section. The variables and parameters settings according to sectors will be explained in the section 3.2.3 to 3.2.5.

### **3.2.1 Context of the model**

In this section, we set up a Sectoral Emission Model for energy transition pathways proposition. The Sectoral Emission Model is a national model for mi-long or long-term period. In this work, the model serves for three types of country that may be considered to represent a number of other similar countries in the world: China, France, and the United States. China and the United States are nowadays two most important emitters of CO<sub>2</sub> in the world, which represent in total more than 40% of the global emissions. France is a representative country with low emissions that can be seen as a benchmark for the big emitters.

The figure 3.1 presents the CO<sub>2</sub> emissions and per capita CO<sub>2</sub> emissions of these three countries from 1971 to 2010. The left axis shows the CO<sub>2</sub> emissions in million tonnes, and the right axis shows the per capita CO<sub>2</sub> emissions in tonnes. From 1971 to 2005, the United States were the biggest sources of CO<sub>2</sub> emissions. After 2006, China took the lead place, with an annual growth rate of 9%. Different from these two

countries, the emissions in France decreased slightly. As shown by the level of per capita emissions, the United States have the highest value at 17t in 2010, which slightly decreased in the last few years. In France, the per capita emissions decreased from 8.5t (in 1971) to 5.5t (in 2010). While in China, the per capita emission increased from less than 1t in 1971 to the same level as France in 2010.



**Fig.3.1. National CO<sub>2</sub> emissions and their per capita CO<sub>2</sub> emissions between 1971 and 2010**

The Sectoral Emission Model is proposed to evaluate the scientific relevance and feasibility of the CO<sub>2</sub> emission scenarios with respect to the population, economy and CO<sub>2</sub> emissions between 2010 and 2050, under the consideration of energy technology transition.

There are three sectors considered in our model: (i) electricity-generation, (ii) transport, and (iii) other, which includes principally the residence and industry sector. The table 3.1 shows that these sectors cover more than 80% of the emissions from fuel combustions in the three countries.

The power sector is the most important emitter in China and in the United States, due to the large amount of fossil fuels combustion. However in France, this sector accounts for only 15% of the total emissions, as about 80% of the power is generated by nuclear plants. The transport sector is also an important emitter, which accounts for 35% of emissions in France, and 30% in the United States. Even though the transport sector accounts for only 7% of CO<sub>2</sub> emissions in China in 2010, the emissions from this sector



will grow rapidly as a result of the rapid growth of car consumptions. The residence and industry sectors represent 36% of emissions in China, primarily from the manufacturing industries and constructions. With the fast urbanization, the energy consumption will rapidly grow in the residence sector. The residence and industry sectors account for 33% in France, with an equal contribution for each sector to the emissions, comparing with 16% for the United States.

From table 3.1, we can observe that the emissions were distributed almost homogenously across sectors in France in 2010. Thanks to the low emissions in the power sector, the consumption of electricity due to the development of other sectors will not add supplementary emissions to the power sector.

**Tab.3.1. Sectoral emissions shares in 2010**

	<b>China</b>	<b>France</b>	<b>the United States</b>
<b>Power</b>	49.28%	15.38%	43.02%
<b>Transport</b>	7.08%	34.56%	30.21%
<b>Residence</b>	4.18%	15.94%	5.99%
<b>Industry</b>	32.15%	17.49%	10.94%
<b>Total</b>	92.68%	83.37%	90.16%

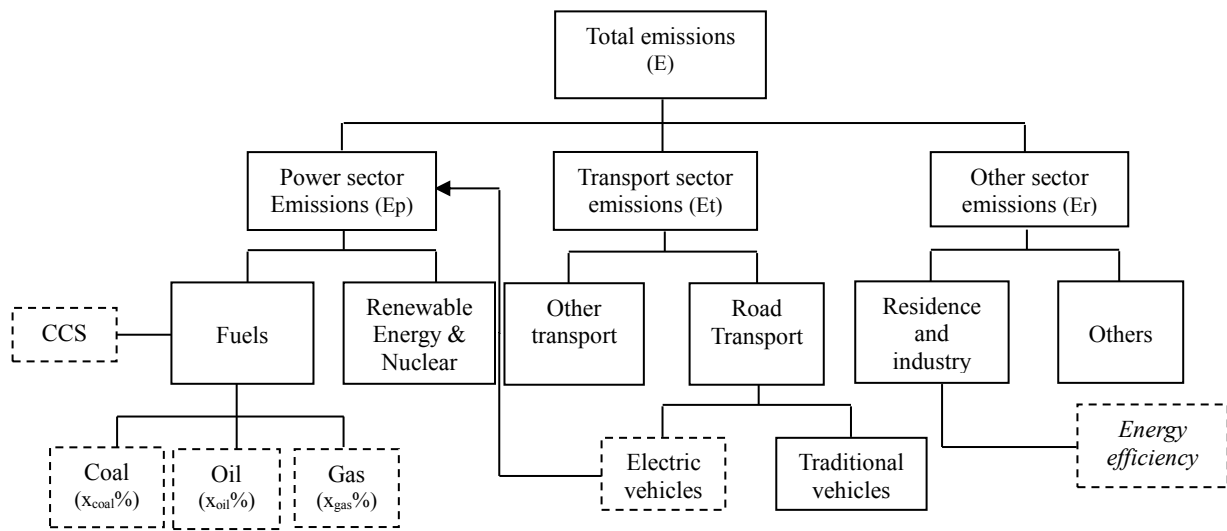
The energy related technologies considered in this work are taking the power and transport sectors as the principal sources of CO<sub>2</sub> emissions. Energy structure, CCS, electric vehicles and energy efficiency are the key parameters in reducing CO<sub>2</sub> emissions. In this context, we here attempt to uncover the right measures to match the scenarios we set out and attain governmental target and global warming objectives. With this objective, the Sectoral Emission model is set up, and its framework will be presented in the following section.

### **3.2.2 Model framework**

The Sectoral Emission Model focuses on three types of sectors: the power sector, the transport sector, and the residence and industry sector. For the power sector, the

electricity could be produced from different energy sources. The sources that produce CO<sub>2</sub> emissions are mainly fossil fuels, namely coal, oil and gas. The sources that produce few emissions, called clean energy, are renewable energies and nuclear energy. In the transport sector, we focus on the road transport, which generally accounts for more than 80% of the transport sector emissions. And in the other sectors, we study mainly the residence and industry sectors.

The structure of the model is presented in the figure 3.2 (Tian and Da Costa, 2013, 2014b):



**Fig.3.2. Schema of Sectoral Emission Model**

As shown in the schema of the Sectoral Emission Model above, the total CO<sub>2</sub> emissions are the sum of the emissions from power sector, transport sector, and the other sectors. Thus the national CO<sub>2</sub> emissions can be written as:

$$E_{(t)} = E_{P(t)} + E_{T(t)} + E_{R(t)} \quad (3)$$

where  $E_{(t)}$  is the total CO<sub>2</sub> emissions from fuel combustions in year  $t$ , and  $E_{P(t)}$ ,  $E_{T(t)}$  and  $E_{R(t)}$  are CO<sub>2</sub> emissions in the corresponding three sectors in year  $t$ .

The technologies to be studied in the model are shown in dotted line in the figure 3.2. We principally analyze the power and transport sectors here, in which fuel mix, CCS and electric vehicles are three key factors behind CO<sub>2</sub> emissions. Improved energy efficiency in the domestic and industrial sector also contributes to CO<sub>2</sub> emission

mitigation. The parameters and variables in the modeling will be explained according to sectors, in the following sub-section.

### 3.2.3 The power-generation sector

In the power sector, we employ the IPAT identity methodology to study the driving forces of the CO<sub>2</sub> emissions in producing electricity from the fuel combustions. The IPAT identity was developed as a general approach for discussing the driving forces behind environmental impacts, which relates impacts (I) to population (P) multiplied by affluence (A) and technology (T), formulated as

$$CO_2 \text{ emissions} = Population * \frac{GDP}{Population} * \frac{CO_2 \text{ emissions}}{GDP} \quad (4)$$

The IPAT identity had been developed later into Kaya identity (Kaya, 1989) which is widely used for CO<sub>2</sub> emissions in many studies, such as the IPCC (2007) assessment report, and the IEA (2008) Energy Technology Perspective report, etc. According to this identity, the CO<sub>2</sub> emissions can be decomposed into the product of three basic factors: carbon intensity of energy, energy intensity and affluence:

$$CO_2 \text{ emissions} = Population * \frac{GDP}{Population} * \frac{Energy \text{ consumption}}{GDP} * \frac{CO_2 \text{ emissions}}{Energy \text{ consumption}} \quad (5)$$

Inspired from the IPAT identity and Kaya identity, we decompose the CO<sub>2</sub> emissions in the power sector into the product of the output of electricity and the technology (i.e. the CO<sub>2</sub> emission intensity of production). And the fossil fuels, such as coal, oil and gas, are the three main sources contribute to CO<sub>2</sub> emissions in the power sector. Analytically, its emissions in year  $t$  are divided into these three categories as follows:

$$E_{P(t)} = (Q_t * \sum x_{i,t} * e_{i,t}) * \epsilon(ccs) \quad (6)$$

where  $Q_t$  is electricity output in year  $t$ ,  $x_i$  presents the three main fuels: coal, oil

and natural gas; equally  $e_i$  is the CO<sub>2</sub> emissions from using coal, oil and gas respectively, and  $\epsilon(\text{ccs})$  the dummy variable.

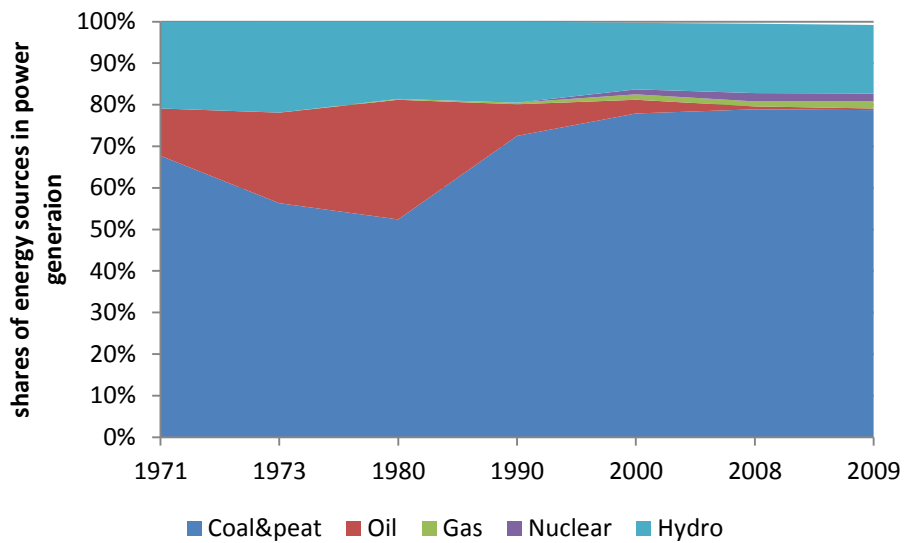
In the modeling of the power sector, energy mix and CCS are the two main technologies to be studied. Besides, the emission intensity of production and electricity output are two important factors in the modeling. The SVR model is thus used to simulate the projection of electricity output.

The variables and parameters in the power sector will be presented in the following four parts: first, the actual energy mix in the three countries is introduced. In the second part, the parameter setting of CO<sub>2</sub> emission intensity of production is discussed. Then the projection of electricity output will be presented in the third part. And the CCS technology will be described in the last part.

### **3.2.3.1 Energy mix**

**China** has abundant coal reserves, while its oil, natural gas and other fossil energy resources are limited. Coal is currently the dominant power fuel. In the end of 2010, thermal power accounted for 73.4% of total power-generation capacity (IEA, 2011a). Without very significant technology breakthrough in power generation, coal-fired power is expected to remain the main source of electricity over the coming 40 years. At the same time, hydropower, nuclear power, and wind and solar power will become increasingly important, with natural gas generation serving as a supplementary power source. Up to 2030, coal generation and hydropower capacity will steadily increase. The Chinese government has proposed a low-carbon development strategy in order to meet increasing energy demand over the next 40 years. In 2050, power-generation technologies are expected to be more efficient and diversified (ERI, 2010).

The historical energy mix in the power generation over 1971-2010 in China is presented in figure 3.3. After 1980, the consumption of coal increase rapidly. The power is generated by coal combustion increased from 50% in 1980 to nearly 80% in 2009. The second source is the hydropower, which accounted for nearly 20% of the power production. However, gas accounted for only 1.7% in 2009.

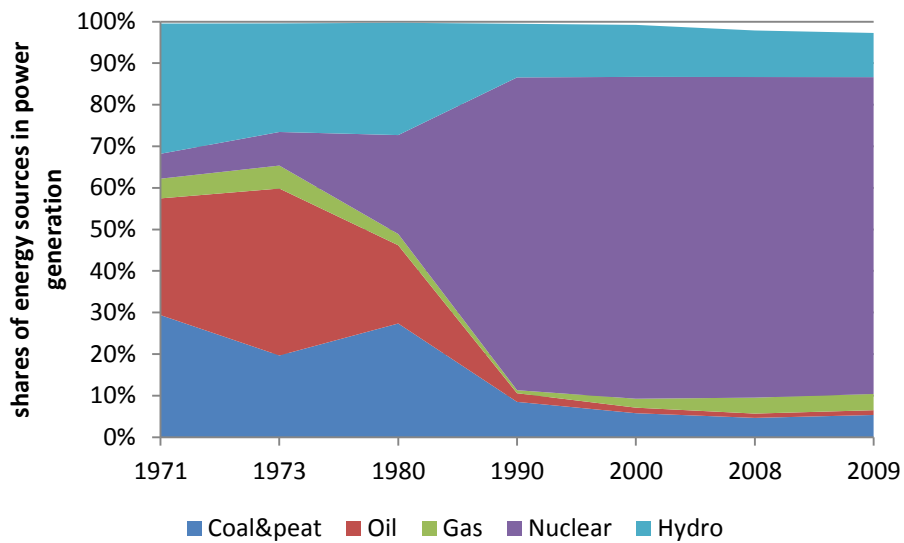


**Fig.3.3. Shares of energy sources in the electricity generation in China, 1971-2009 (IEA, 2012)**

**France** is one of the least CO<sub>2</sub> intensive industrialized economies, thanks to the substantial role of nuclear power and the existence of higher gasoline taxes with incentive impacts. CO<sub>2</sub> emissions have been declining since 2005 from an already relatively low base. By 2007, France had reduced its total CO<sub>2</sub> emissions below its Kyoto target<sup>15</sup>. In 2009, nuclear power accounted for 76.24% of France's electricity generation and over 40% of the Total Primary Energy Supply (TPES). France imports nearly all of its oil, gas and coal requirements, but its fossil-fuel imports are well diversified. The current share of gas in TPES in France is lower compared with other IEA European countries. In 2008, natural gas accounted for nearly 15% of TPES, up from 12% in 1990, but still well below the IEA European average of 25%.

The French government projects that the share of gas in the power sector will increase from under 4% currently to cover 10% in 2020. Oil use for power generation is minimal and accounts for only 1.1% of total electricity generation. The share of renewable energy in electricity production in 2007 was 12%, with hydropower accounting for over 85% of this figure. The figure 3.4 depicts the shares of the main sources of electricity generation over 1971-2010.

<sup>15</sup> In the Kyoto Protocol, CO<sub>2</sub> emissions from fuel combustions in France should be limited under the increase of 0.6% between 1990 and 2009.



**Fig.3.4. Shares of energy sources in the electricity generation in France, 1971-2009 (IEA, 2012)**

**The United States** depends on fossil fuels for almost all its energy supply. Natural gas use is rapidly growing in the United States, particularly for the power generation, where it has now overtaken nuclear to become the second most important power-generation fuel. Coal is also an important fuel in the United States, accounting for half of the country's electricity generation, and contributing in particular to the economies of the Western states. CO<sub>2</sub> emissions in the United States rose by 16% between 1990 and 2005.

The shares of the main energy sources for power generation are depicted in figure 3.5. After 1990, the share of gas used in the power production increased to 23% in 2009. Meantime, the utilization of coal has reduced to 45%.

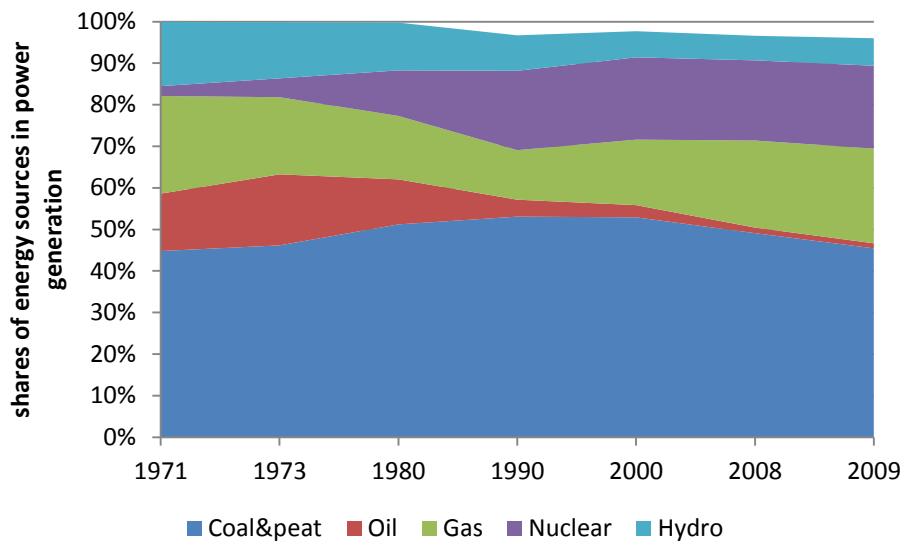


Fig.3.5. Shares of energy sources in the electricity generation in US, 1971-2009 (IEA, 2012)

### 3.2.3.2 CO<sub>2</sub> emission intensity of production

As a result of the different energy mix in the power sector, CO<sub>2</sub> emissions per KWh (the CO<sub>2</sub> emission intensity of production) from electricity generation vary greatly across countries. The figure 3.6 shows that CO<sub>2</sub> emissions per KWh in France are only 12% of the level in China and 20% of the level in the US over 1990 - 2010, as coal plays a dominant role in China and the United States, while nuclear power plants currently account for 80% of French electricity output.

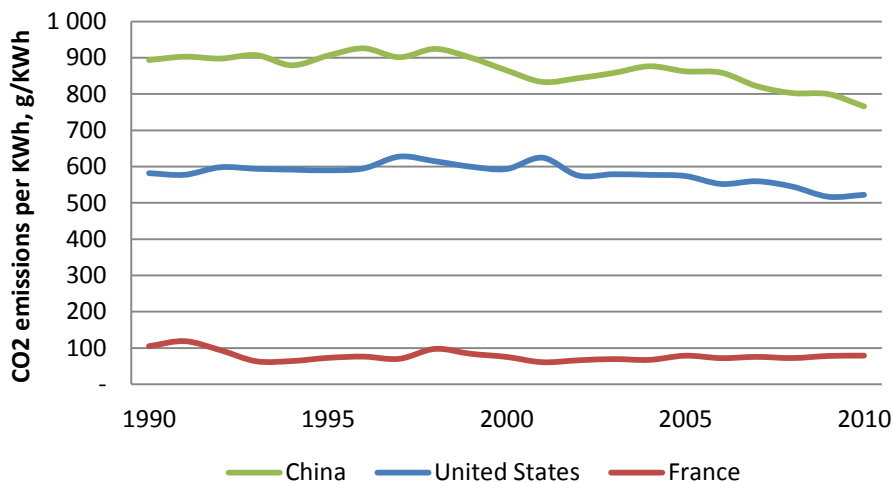


Fig.3.6. CO<sub>2</sub> emissions per KWh from electricity generation

The emission intensity of production of each fuel varies widely between countries according to the different types of energy and technology levels, as shown in the table 3.2. The emission intensities of production of fuels are the lowest in Europe, so we adopt the emission intensities of production in 2010 of Europe as the intensities of production for the three countries in 2050, which are 0.8kg/kwh for coal, 0.4kg/kwh for oil, and 0.2kg/kwh for gas.

**Tab.3.2. CO<sub>2</sub> emission intensities of production of fossil fuels (IEA, 2012)**

<b>Kg/KWh</b>	<b>coal</b>	<b>oil</b>	<b>gas</b>
<b>China (2010)</b>	0.967	1.044	0.507
<b>France (2010)</b>	0.949	0.766	0.520
<b>The United States (2010)</b>	0.907	0.711	0.405
<b>Europe (2010)</b>	0.8	0.4	0.2

### **3.2.3.3 Electricity output**

As to the electricity production, we will make the projection with the historical data between 1971 and 2010. We choose the Support Vector Regression (SVR) to carry out the simulation, because SVR is an appropriate model for small databases.

SVR has successfully been tested to solve forecasting problems in many fields, such as financial time series forecasting (Cao, 2003) and electric load forecasting (Hong, 2010; Wang et al., 2009), amongst others. Based on this work, we used SVR to make predictions for electricity production and pollution intensity.

SVR comes from the Support Vector Machine (SVM). The SV algorithm is a nonlinear generalization of the Generalized Portrait algorithm of the 1960s. The formulation of SVM embodies the Structural Risk Minimization (SRM) principle, which has been shown to be superior to Empirical Risk Minimization (ERM). SVMs were first developed to solve the classification problem, in which it is shown that the generalization error is bounded by the sum of the training set error and a term depending on the Vapnik-Chervonenkis dimension of the model (Cortes and Vapnik, 1995; Gao et al., 2002). When SVM is used for regression (especially non-linear



regression), it is called a Support Vector Regression (SVR). SVR can estimate the nonlinear relationship between the data and produces good results after mapping the input data into a high-dimensional Reproducing Kernel Hilbert Space (RKHS), as compared to other commonly-used techniques.

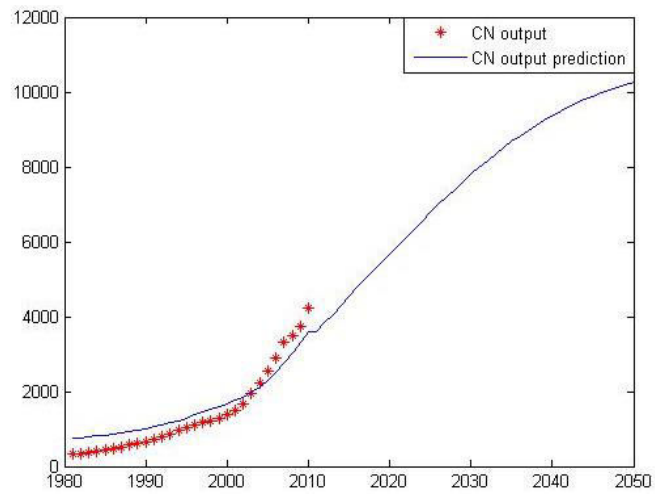
SVR is used to provide the underlying function in each country. There are different kinds of SVR according to the different loss functions and kernel functions employed. We here use the  $\varepsilon$ -insensitive function and an appropriate kernel function for each country and variable by trial and error. Some critical parameters related to the loss function and kernel function need to be tuned before the training and prediction of the model. Details regarding the tuning of the parameters and kernel functions can be found in (Liu et al., 2013).

In our work here, the data sets are all normalized from the raw data. We use a sigmoid kernel function for electricity-production prediction. The Polynomial kernel Function  $(\gamma * \vec{u} \cdot \vec{v} + \text{coef})^{\text{degree}}$  is used as the kernel function for electricity output by trial and error. The values of the related hyperparameters are also turned with a Grid Search. The parameters are listed in the table 3.3:

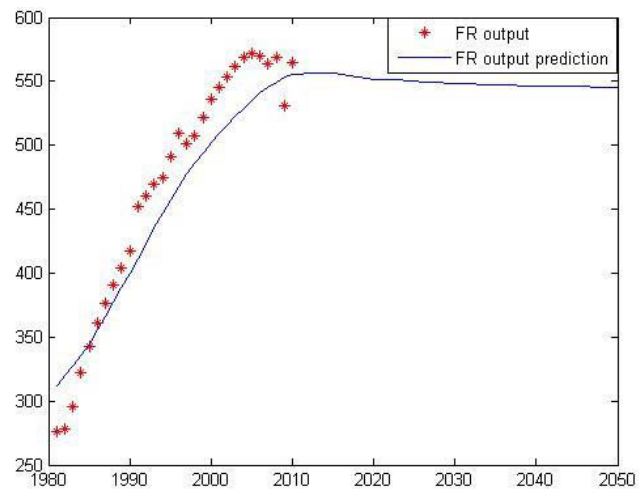
**Tab.3.3. Values of the hyperparameters in electricity output**

	<b>C</b>	<b>Degree</b>	$\xi$	<b><math>\gamma</math></b>	<b><math>R^2</math></b>
<b>China</b>	1	4	1.0E <sup>-3</sup>	10	0.6478
<b>France</b>	1	4	1.0E <sup>-3</sup>	10	0.7161
<b>United States</b>	1	4	1.0E <sup>-3</sup>	10	0.7196

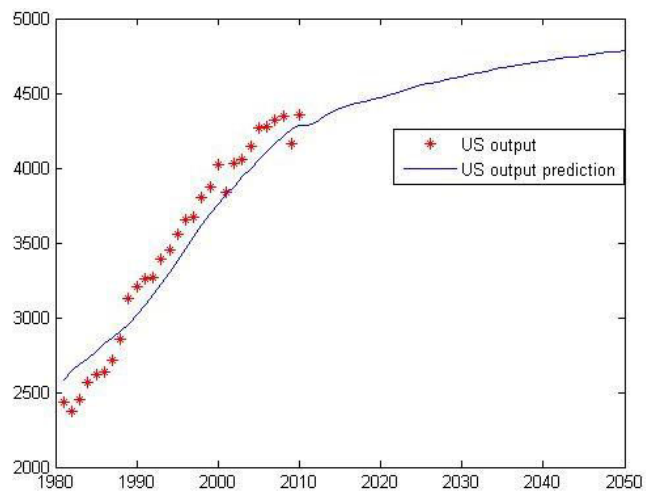
The electricity-production simulation results are based on the data of 1971-2010 (IEA, 2012). Chinese electricity output will be 10248TWh in 2050, a 2.43-fold rise over 2010. In France it will be 539TWh in 2050 (a 4% fall from 2010), and 4785TWh (a 10% rise over 2010) in the United States. Figures 3.7 to 3.9 show the projection of electricity production in the three countries between 1981 and 2050. The X-axis is in years and the Y-axis is electricity output in TWh.



**Fig.3.7. Electricity production in China 1981-2050**



**Fig.3.8. Electricity production in France 1981-2050**



**Fig.3.9. Electricity production in the US 1981-2050**

### **3.2.3.4 Carbon dioxide Capture and Storage technology**

Besides improving the emission intensities of production of fossil fuels, CCS is considered as one of the potential options for reducing atmospheric CO<sub>2</sub> emissions from human activities. As CO<sub>2</sub> is emitted principally from the burning of fossil fuels, especially from the large combustion units such as those used for electric power generation, CCS would most likely be applied to large point sources of CO<sub>2</sub>, like the power plants. CCS involves the use of technology, first to collect and concentrate the CO<sub>2</sub> produced in energy-related sources, transport it to a suitable storage location, and then store it away from the atmosphere for a long period of time. CCS would thus allow fossil fuels to be used with low GHG emission.

CCS has not been used in large-scale power plants, so there is relatively little experience with the combination of CO<sub>2</sub> capture, transport and storage in a fully integrated CCS system. The wide range of costs for CCS systems is primarily due to the variability of sit-specific factors, the type and costs of fuel used, the required distances, terrains and quantities involved in CO<sub>2</sub> transport, and the type and characteristics of the CO<sub>2</sub> storage. In most CCS systems, the cost of capture is the largest cost component, in the range of 15-75 US\$/tCO<sub>2</sub> net captured from a coal- or gas-fired power plant. The cost of transportation is between 1 US\$/tCO<sub>2</sub> and 8 US\$/tCO<sub>2</sub>. The cost of storage is 0.5-8 US\$/tCO<sub>2</sub> for geological storage and 5-30 US\$/tCO<sub>2</sub> for ocean storage.

According to the “Carbon Dioxide Capture and Storage: Technical Summary” of IPCC (2005), if the CCS is equipped with the power plant, about 90% of the CO<sub>2</sub> emissions will be captured and stocked. Thus, we have the dummy variable  $\epsilon(\text{ccs})$  to the equation 6, where:

$$\epsilon(\text{ccs}) = \begin{cases} 0.1, & \text{90\% emissions be absorbed with CCS} \\ 1, & \text{no emissions be absorbed without CCS} \end{cases}$$

## **3.2.4 The transport sector**

The power generation sector makes the most important contribution to the global

CO<sub>2</sub> emissions, and the second most important emitter is the transport sector. The transport sector was responsible for approximately 23% of the global energy-related CO<sub>2</sub> emissions in 2010, of which 72% CO<sub>2</sub> emissions come from road transport. Thus, we will focus on the road transport in the transport sector emissions, the most important emission source in the transport sector.

In this section, we will first introduce key technology in the road transport sector, which is the low-carbon emission vehicle. Then, the situation of transport emissions in the three countries chosen and the modeling method in this sector will be presented.

#### **3.2.4.1 Road transport vehicles**

Reducing global transport GHG emissions will be challenging since the continuing growth in passenger and freight activities. According to IEA statistics, the transportation sector accounted for over 40% of oil demand in 2010. Oil use will become increasingly concentrated in the transportation sector, reaching 65% of total oil demand in 2035, according to the *New Policy Scenario of the World Economic Outlook 2011*. Thus, automobiles with clean energy sources are encouraged to replace the traditional gasoline and diesel ones.

Hybrid vehicles and electric vehicles are two emerging technologies that manufacturers are increasingly turning towards, especially for the electric vehicles. Hybrid vehicles (conventional hybrids, Plug-In Hybrid Electric Vehicles) combine both an electric motor and a gasoline engine. Electric vehicles (Plug-In Electric Vehicles, Battery Electric Vehicles and Fuel Cell Electric Vehicles) use an electric-only motor but with different energy storage systems. Electric vehicles have no direct tailpipe emissions, the indirect emissions come from charging the vehicle's battery with grid electricity generated by fossil fuels powered power plants. Thus, electric vehicles have a CO<sub>2</sub>eq reduction cost highly correlated to the carbon intensity of electricity generation. However, with the transformation of power sector, the indirect emission will reduce in long-term. In this context, we choose electric vehicles as the option for the technology transition in the transport sector modeling. Along with the advantages of electric vehicles, there are barriers for the adoption, such as high battery costs, willingness of

consumers, charging facility and so on. The penetration of the market and the technology advancement need the encouragement of government.

#### ***3.2.4.2 Road transport emission across the three countries***

The transport sector is responsible for the largest share of CO<sub>2</sub> emissions in France (over one third of emissions in 2010), with road transport accounting for 96% of transport emissions. Thanks to its low-cost low-carbon electricity supply, France could be able to reduce transport emissions by focusing on electricity-based technologies, such as high-speed rail and electric vehicles. Actually, there are about 30 000 electric vehicles in France, which account for 0.08% of all the vehicles. The energy transition law (“la loi de la transition énergétique”) was adopted on 2014, which announced that the bonus for changing to electric vehicles can be accumulated up to 10 000 euros, and the government will install charging stations all over the France, with the objective to a total number of 7 million in 2030.

In 2010, the United States had the most vehicles of any countries in the world (254 million), with transport accounting for 30% of CO<sub>2</sub> emissions, of which road emission was responsible for 86.4%. In 2009, the President of the US pledged US\$2.4 billion in federal grants to support the development of next-generation electric vehicles and batteries. And as part of the American Recovery and Reinvestment Act, the US Department of Energy announced the release of two competitive solicitations for up to \$2 billion in federal funding for competitively awarded cost-shared agreements for manufacturing of advanced batteries and related drive components as well as up to \$400 million for transportation electrification demonstration and deployment projects. This initiative aimed to help meet President's goal of putting one million plug-in electric vehicles on the road by 2015. In 2014, nearly 120 000 electric vehicles were sold in the US.

In China, transport accounts for only 7% of total emissions in 2010. With a growth rate in the number of vehicles of 11% in 2010, transport, and especially road transport, will be increasingly important for future CO<sub>2</sub> emissions. Thus, it is critical for China to develop electric vehicles. There were 4 400 electric vehicles up to 2012. In order to

encourage the consumers, 5 billion yuan was allocated as the total allowance for the purchasing of electric vehicles from 2009, and 5 million electric vehicles are expected to be used in 2020.

With current technology, an electric vehicle consumes 0.01 KWh/km to 0.03 KWh/km. Here, we employ the mean value of 0.02 KWh/km, that is 0.73MWh/yr (shown in equation 8), which makes a notable contribution to total electricity output.

The CO<sub>2</sub> emissions of the transport sector in year  $t$  are then calculated as:

$$E_{T(t)} = \frac{E_{road(t)}}{\alpha_{road}} = \frac{E_{road(2010)} * (1+\gamma)^t * (1-y_t)}{\alpha_{road}} \quad (7)$$

where  $E_{T(t)}$  are CO<sub>2</sub> emissions in the transport sector in year  $t$ ,  $E_{road(t)}$  are CO<sub>2</sub> emissions from road transport in year  $t$ ,  $\gamma$  is the vehicle growth rate,  $y_t$  is the proportion of hybrid vehicles in the vehicle stock in year  $t$ , and  $\alpha_{road}$  is the share of road transport in the CO<sub>2</sub> emissions of the transport sector. The baseline CO<sub>2</sub> emissions in the road transport will increase from 400mt in 2010 to 1968mt in 2050 in China, due to the fast growth of car numbers. The baseline CO<sub>2</sub> emissions in France will increase from 118mt to 198mt, and from 1400mt to 2170mt in the United States.

The use of hybrid vehicles will definitely increase electricity production, as described below:

$$E_P^{tr} = 0.73 * y_t * N_{(t)} \quad (8)$$

where  $N_{(t)}$  is the stock of vehicles in year  $t$ . Total electricity output is therefore:  $E_{P(t)} + E_P^{tr}$ . For the number of vehicles in 2050, we assume that it will keep increasing at the growth rate in 2010 at about 1% in France and in the United States, as their car number growth was at a stable rate<sup>16</sup>. However, because the car numbers were increasing fast in the past few years in China, we assume that the cars numbers will

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<sup>16</sup> The projections of car numbers in France and the United States are more optimistic than in the IEA “Energy Technology Prospective” report in 2014, where the car numbers are assumed to be nearly unchanged in the 6DS (baseline) scenario. However, the car number projections in different studies can be controversial in terms of various assumptions. For example, the personal car numbers in 2050 are projected to be about half of that in 2010 according to the projection of ANCRE. Thus, in this work, we project evolution of the car numbers in these countries following their historical growth trends, without involving other parameters in order to make a simplified and clear assumption.

increase first at a rapid rate as in 2010 at 10%, and then this growth rate will progressively decrease to 1% in 2050<sup>17</sup>.

The numbers of vehicles in 2050 in these countries are shown in the table 3.4. In this assumption, the vehicles in China will increase much more than the other two countries, from 114 million to 560 million in 2050, which is at the same level as in 6DS scenario (baseline scenario) in the IEA (2014) “Energy Technology Prospective” report. Thus every ten person will have 4 cars, which corresponds to one vehicle for one family. The car numbers will rise from 38 million to 63 million in France, and from 269 million to 393 million in the United States, which means nearly one vehicle for one person.

**Tab.3.4. Assumptions for number of vehicles in 2050**

	<b>Number of vehicles in 2010 (million)</b>	<b>Number of vehicles in 2050 (million)</b>	<b>Number of vehicles per person in 2010</b>	<b>Number of vehicles per person in 2050</b>
<b>China</b>	114	560	0.085	0.4
<b>France</b>	38	63	0.6	0.9
<b>United States</b>	268	393	0.86	0.98

### **3.2.5 The domestic and industrial sector**

In the Sectoral Emission Model, we primarily focus on the two most important emission sectors, which are power and transport sectors. Amongst the other sectors, we consider primarily domestic and industrial consumption because these two sectors account for most of emissions in the other sectors. Improving the energy efficiency is the key technology for reducing GHG emissions in the two sectors. In this section, we will not consider all the energy efficiency technologies into the Sectoral Emission Modeling, but, the notion energy efficiency, which is employed to be the representative technology.

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<sup>17</sup> The projection of car numbers in China in 2050 is at the same level than in the IEA “Energy Technology Prospective” report in 2014, in the 6DS (baseline) scenario.

### 3.2.5.1 Energy efficiency related technologies

The energy use and related emissions in the domestic sector will increase, especially in the developing countries, with the increasing need for adequate housing, electricity, and improved cooking facilities. For the industrial sector, despite its declining share in global GDP, the GHG emissions from the industrial sector keep increasing, especially in the developing countries. In 2010, domestic CO<sub>2</sub> emissions accounted for 22.4% of those in the other sectors in the United States; in France and China, this figure was 31.8% and 9.6% respectively. Domestic and industrial energy consumption can be reduced by improving energy efficiency.

Energy efficiency is a general notion which means to consume less energy in providing the same service. Many potential technologies are available for improving the energy efficiency. For example, more efficient appliances, smart meters and grids, fuel-switching to low-carbon fuels such as electricity or biomass, more efficient isolation in the buildings, etc. As to the industrial sector, the energy efficiency involves fuel-switching to low-carbon fuels, efficient process heating systems, material recycling, etc. For developing countries, there are still many energy efficiency options both for process and system-wide technologies and measures.

CO<sub>2</sub> emissions in the rest sectors other from power sector and transport sector are presented as follows:

$$E_{R(t)} = \frac{E_{RI(t)}}{\beta} = \frac{(1-e)*E_{RI(baseline)}}{\beta} \quad (9)$$

where  $E_{R(t)}$  is CO<sub>2</sub> emissions from the other sectors in year  $t$ ,  $E_{RI(t)}$  is domestic CO<sub>2</sub> emission,  $e$  represents the improvement of domestic energy efficiency,  $E_{RI(baseline)}$  is domestic CO<sub>2</sub> emission without taking energy efficiency into account, and  $\beta$  is the domestic share in other sector CO<sub>2</sub> emissions. The baseline domestic CO<sub>2</sub> emissions in China will increase from 303mt in 2010 to 458mt in 2050, and they will increase from 322mt to 430mt in the United States. However, the baseline emissions in the domestic will be reduced from 57mt to 39mt in France, because of the decreasing trend of CO<sub>2</sub> emissions in the past few years.



## 3.3 Data and scenarios

In the former section, we have explained the structure of the Sectoral Emission Model, and presented the variables and parameters for the modeling. In this model, we use target-oriented scenarios for CO<sub>2</sub> emissions, which are Business-as-Usual scenarios, 3°C scenarios, 2°C scenarios, and governmental target, for the technology roadmaps. The 3°C and 2°C scenarios are established by IPCC, and the governmental targets are announced by the three countries. As to the Business-as-Usual scenarios, they will be simulated in terms of different situation of the three countries. According to the IPAT equation, the CO<sub>2</sub> emissions are the results of population, economy and technology. Thus, the use of population and GDP are indispensable in simulating the CO<sub>2</sub> emissions in the Business-as-Usual scenario.

In this section, the data of population and GDP are firstly presented, and then the scenarios of CO<sub>2</sub> emissions used in the modeling are introduced.

### 3.3.1 Data assumptions

#### *3.3.1.1 Data of population in 2010-2050*

As human is the primary factor in consuming the energy resources, the evolution of the population is a key factor in studying the CO<sub>2</sub> emissions. The population scenarios are generated from the United Nations' World Population Prospects 2012 (WPP) (United Nations Population Division, 2013). The scenarios are divided into four population-growth categories: high variant scenario, medium variant scenario, low variant scenario and constant-fertility variant scenario. In this work, we adopt the medium variant scenario for the population projection data, in order to avoid the extreme values in the projection.

The population projections of China, France and the United States in 2050 are shown in the table 3.5. According to this scenario, the population in China will have a

peak at around 2025, after which it will fall by 4%, from 1.34 billion to 1.29 billion (see the *one child policy* of the 1980s). In France, the population will increase by 15%, from 62 million to 72 million. In the United States, the population grows the most among the three nations. It will increase by 30%, from 310 million in 2010 to 403 million in 2050. The population's global shares in 2010 and 2050 are also shown in this table. The share of population in the three countries will all decrease in 2050 compared to 2010. In France, it will decrease by 17%, in the United States by 7%, and in China by 30%.

**Tab.3.5. Population scenarios by medium variant in 2050**

<b>Population</b>	<b>China</b>	<b>France</b>	<b>The United States</b>	<b>World</b>
<b>2050 (million)</b>	1 295.604	72.442	403.101	9 550.945
<b>2050 (world share)</b>	13.57%	0.76%	4.22%	
<b>2010 (million)</b>	1 341.335	62.787	310.384	6 825.4
<b>2010 (world share)</b>	19.65%	0.92%	4.55%	

### **3.3.1.2 Data of GDP in 2010-2050**

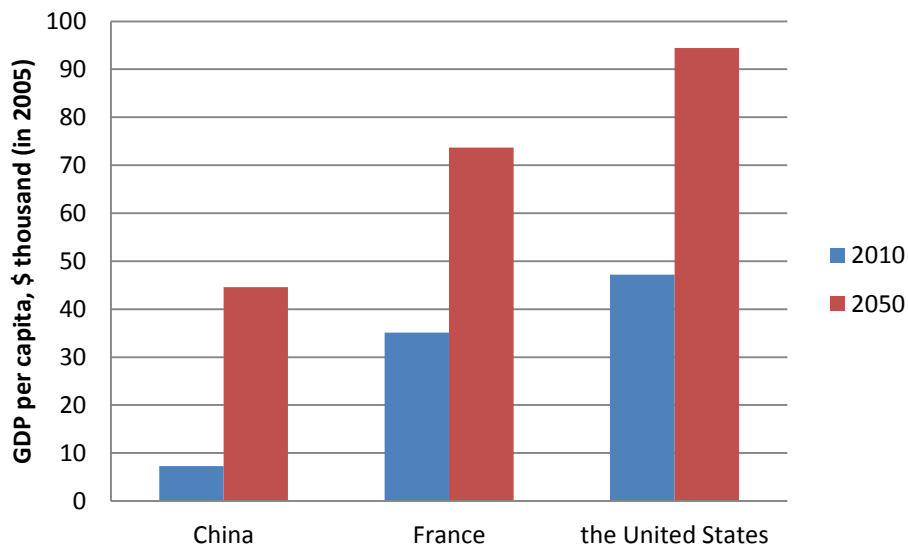
Besides the population, the economy also plays an important role in the energy utilization. The increase of average income will definitely stimulate the personal energy consumption. The economy had different growth rate in the developed and developing countries over 1971-2010. The GDP using Purchasing Power Parities (PPP) in the United States has increased from \$4 359 billion to \$13 017 billion, with an average rate of 2.7%. The GDP in France has increased from \$820 billion to \$1923 billion, with an average rate of 2.1%, and it increased from \$332 billion to \$9417 in China, with an average growing rate at 8.7% (IEA, 2012). The table 3.6 presents the economy in the Baseline scenario in the three countries, according to the report "The world in 2050" (HSBC, 2011).

**Tab.3.6. GDP (PPP) Baseline scenarios in 2050**

<b>GDP ppp (billion dollars)</b>	<b>China</b>	<b>France</b>	<b>The United States</b>
<b>2050</b>	57 784.54	5 339.13	38 060.89
<b>2010</b>	9 785.54	2 204.68	14 655.48

The GDP in the Baseline scenario indicates future economic development under current policy circumstances, which can be considered as the continuation of the historical trend. In this scenario, the growing rate of GDP in China will gradually decrease from 8% to 3% in 2050. Thus, the average annual growth rate will be at 4.5% in China. As to France and the US, the economy will grow stably, at 2.2% in France and at 2.4% in the United States.

Note that even with a forecasted fast economy increase in China to 2050, the per capita GDP (average income) is still lower than that of France and the United States. The figure 3.10 shows the per capita GDP of the three countries in 2010 and 2050. The per capita income in China in 2010 was \$7 000, and it will increase by more than 5 times to \$44 000 in 2050. But it is still lower than the per capita GDP in France and in the United States, which are expected to be \$73 000 and \$94 000, respectively.



**Fig.3.10. projected GDP per capita in 2050**

### 3.3.2 CO<sub>2</sub> emission scenarios

There are hundreds scenarios of CO<sub>2</sub> emissions, as presented in Chapter 2. In this work, we adopt three categories of target-oriented CO<sub>2</sub> emissions scenarios:

- 1) The Business-as-Usual scenario;

- 2) The world reference scenarios, which are 3°C scenario by grandfathering, 3°C scenario by equal emission, 2°C scenario by grandfathering, 2°C scenario by equal emission;
- 3) The Policy scenario. In this work, we will focus on the Policy scenario, and the other scenarios are set to be different reference scenarios.

The Business-as-Usual scenario is assumed to be under an unchanged policy and technology. This scenario is generated by STIRPAT model according to the historical CO<sub>2</sub> emissions in each of the three countries.

The world reference scenarios are the scenarios from the IPCC report, whose emission targets are allocated by different equity approaches. There are four reference scenarios: the 3°C scenario comes from the IPCC fifth report by group III (IPCC, 2014a) corresponding to the RCP4.5 scenario, which is possible to limit the rise of global temperature under 3°C in 2100. In this scenario, the global emission should be back to the 2010 level. Similarly, the 2°C scenario refers to limit the increase of global temperature under 2°C in 2100 according to IPCC fifth report by group I (IPCC, 2013).

Finally the policy scenario is related to the governmental targets of emission reduction for the countries to 2050. The details of the scenarios are shown as following:

### **3.3.2.1 Business-as-Usual (BaU) scenario:**

In order to project the CO<sub>2</sub> emission in the BaU scenario, we adopt the STIRPAT model to simulate the relationship between CO<sub>2</sub> emissions and the economic and demographic variables.

The STIRPAT model is derived from the IPAT identity, assuming that the factors may have different influences on the environment (Dietz and Rosa, 1994). The STIRPAT technique models statistically the non-proportionate impacts of variables on the environment (Dietz and Rosa, 1997; Lin et al., 2009; Martinez-Zarzoso and Maruotti, 2011; Meng et al., 2012; Wei, 2011; York et al., 2003). The STIRPAT equation is:

$$I_i = a * P_i^b * A_i^c * T_i^d * e_i \quad (10)$$

where  $I$ ,  $P$ ,  $A$ ,  $T$  have the same signification as in the IPAT identity (eq.10);  $i$  indicates the time series;  $a$  defines the scale of the model;  $b$ ,  $c$ , and  $d$ , are the exponentials of  $P$ ,  $A$  and  $T$  respectively; and  $e$  is the error term<sup>18</sup>.

In general the variables are introduced in a logarithmic form in the simulations:

$$\log I = \log a + b * (\log P) + c * (\log A) + \log e \quad (11)$$

The prediction is tested by ordinary least squares (OLS) regression. With data from 1971 to 2010 (IEA, 2012), we predict the BaU scenario up to 2050. The parameters in the STIRPAT equation are presented in the table 3.7:

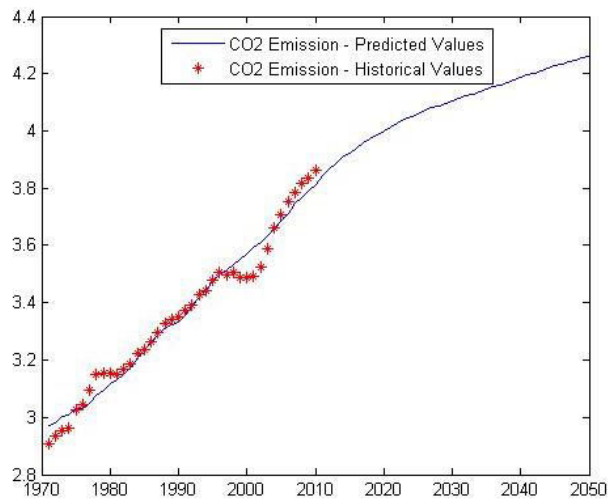
**Tab.3.7. Values of parameters in STIRPAT**

	<b>Constant (loga+loge)</b>	<b>b</b>	<b>c</b>	<b>R<sup>2</sup></b>
<b>China</b>	-0.679 (-0.284)	0.6546 (1.648)	0.5688 (8.468 <sup>***</sup> )	0.9755
<b>France</b>	3.3813 (0.650)	-0.0672 (-0.056)	-0.3416 (-0.929)	0.4338
<b>United States</b>	8.1599 (4.590 <sup>***</sup> ) <sup>19</sup>	-1.0816 (-2.825 <sup>**</sup> )	0.9319 (4.702 <sup>***</sup> )	0.8647

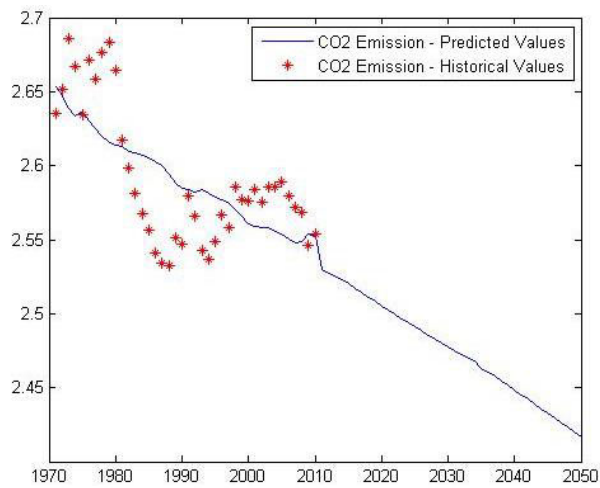
The STIRPAT model projects that the CO<sub>2</sub> emission in 2050 will be 5.75 Gt, 2.1 times of the 2010 level. Figures 3.11 to 3.13 show the logarithm of CO<sub>2</sub> emissions in the three countries between 1971 and 2050. The X-axis is in years and the Y-axis in millions of tonnes.

<sup>18</sup> If  $a = b = c = d = e = 1$ , the STIRPAT reduces to the IPAT identity and  $T$  is included in the error term (unlike in the IPAT identity, where  $T$  serves to balance the equation).

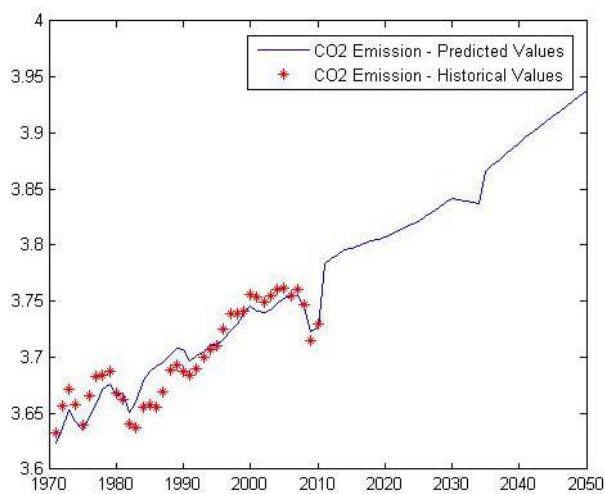
<sup>19</sup> The t-statistics are in parentheses. <sup>\*\*</sup> is the 0.001 significance level and <sup>\*\*\*</sup> the 0 significance level.



**Fig.3.11. Logarithm of CO<sub>2</sub> emissions projections in China, 1971-2050**



**Fig.3.12. Logarithm of CO<sub>2</sub> emissions projections in France, 1971-2050**



**Fig.3.13. Logarithm of CO<sub>2</sub> emissions projections in the US, 1971-2050**

The 3°C scenario and 2°C scenario are evaluated by two allocation methodologies: grandfathering approach and equal emission convergence approach. For grandfathering approach, the emission rights are based on the existing patterns, which is a well-known accounting method often used in the allocation of emissions. For example, this scheme was applied to the developed countries in the Kyoto Protocol, which required them to reduce the emissions related to their levels in 1990. This approach allows the countries who emitted more before to have a larger emission space in the future than the countries which emitted less before.

The equal emission convergence approach seeks to allocate the future emission budgets rights to countries in proportion to their population. This accounting method considers the equality of per capita emissions between the developed and developing countries.

### ***3.3.2.2 World reference scenarios***

- **3°C scenario (grandfathering):**

The CO<sub>2</sub> emissions in 2050 of a country will equal to its emissions level in 2010, which means the emissions will be 7 258mt in China, 357mt in France, and 5 368mt in the United States in 2050.

- **3°C scenario (equal emission):**

The CO<sub>2</sub> emissions in 2050 of a country are proportional to the shares of the global population in 2050. The expected global emission in this scenario is 30 276mt, which means the emissions will be 4 107mt in China, 230mt in France, and 1 278mt in the United States in 2050.

- **2°C scenario (grandfathering):**

The CO<sub>2</sub> emissions in 2050 of a country will equal to half of its emissions in 1990, which means the emissions will be 1 122mt in China, 176mt in France, and 2 434mt in the United States in 2050.

- **2°C scenario (equal emission):**

The CO<sub>2</sub> emissions in 2050 of a country are proportional to the shares of the global population in 2050. The expected global emission in this scenario is 10 487mt, which means the emissions will be 1 422mt in China, 80mt in France, and 442mt in the United States in 2050.

### **3.3.2.3 Policy scenario:**

In 2009, China promised to reduce its CO<sub>2</sub> intensity (CO<sub>2</sub> emission per unit of GDP) by 40%-45% in 2020<sup>20</sup> (ERI, 2009) compared to 2005, and this objective is extenable to 85%-90% in 2050. In this work, we adopt the reduction of CO<sub>2</sub> intensity by 90% in 2050, which means the expected CO<sub>2</sub> emissions are 5 259mt in 2050, with the baseline scenario of GDP assumption.

The U.S. House of Representatives passed the American Clean Energy and Security Act, which aimed to reduce 17% of their CO<sub>2</sub> emissions below the 2005 level in 2020<sup>21</sup>, and 83% in 2050(Waxman and Markey, 2009), which means that their CO<sub>2</sub> emissions are expected to be reduced to 981mt in 2050.

The French government announced a reduction of CO<sub>2</sub> emissions by 75%<sup>22</sup> (“facteur 4”) in 2050 compared to level in 1990 according to “Loi n° 2005-781 du 13 juillet 2005 de programme fixant les orientations de la politique énergétique (POPE)” (ADEME, 2014), which means that the CO<sub>2</sub> emission are expected to be 89mt in 2050. All these governmental targets for reducing CO<sub>2</sub> emissions have not been changed till now.

The propotion of CO<sub>2</sub> emissions in 2050 relative to 2010 under the six scenarios are shown in the figure 3.14. In the BaU scenario, the emissions increase the most in China, which is 250% of its 2010 level, due to the fast growth of emissions in the past

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<sup>20</sup> Actually, in 2013, the CO<sub>2</sub> intensity had been decreased by 28.5% compared to 2005. According to the “Plan for the Climate Change (2014-2020) (in Chinese) ” released in september in 2014 by the Chinese government, the objective of reducing CO<sub>2</sub> intensity in 2020 was not changed.

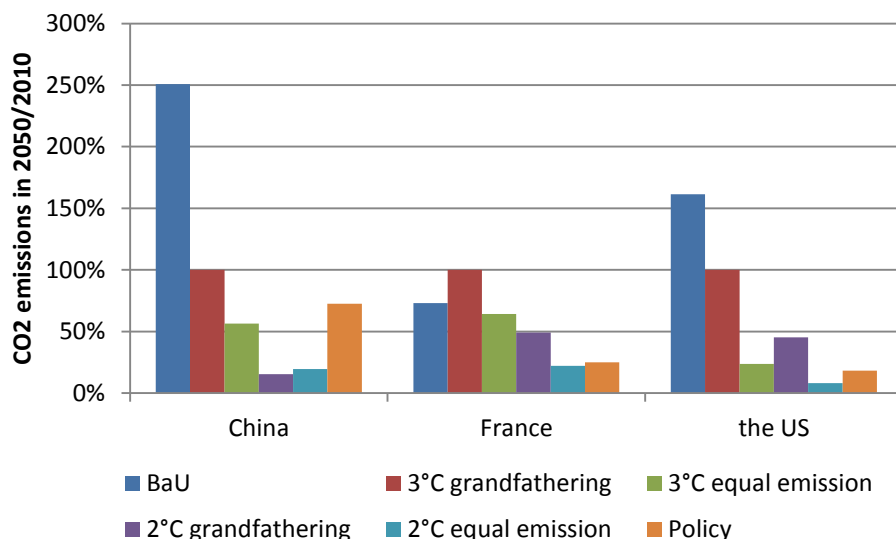
<sup>21</sup> In 2013, the GHG emissions were 9% below 2005 level, according to the “U.S. Greenhouse Gas Inventory Report: 1990-2013”.

<sup>22</sup> In 2012, the CO<sub>2</sub> emissions from the fuel combustions in France were 5.4% less than its 1990 level, according to “Les chiffres clés du climat France et Monde (edition 2015)”.



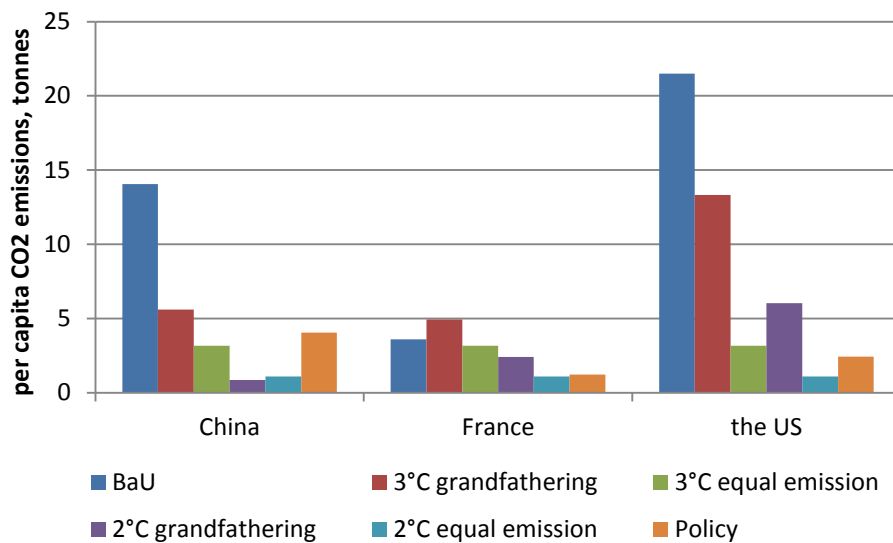
40 years. In the United States, the emissions will increase by 60% in 2050 compared to 2010. Different from the two countries, France will have decreasing emissions, by 27% in BaU scenario, as a results of decreasing emissions in the past few years.

In the 3°C equal emission scenario, the emissions in 2050 will be 57% of that in 2010 in China, 64% in France and 24% in the United States. In the 2°C equal emission scenario, the emissions in 2050 will be 20% of that in 2010 in China, 22% in France and 8% in the United States. Compared to the 2°C equal emission scenario, the Policy scenario is more tolerant, the emissions in 2050 will be 72% of that in 2010 in China, 25% in France and 18% in the United States.



**Fig.3.14. National emissions by scenarios in 2050 compared to the 2010 level**

In terms of per capita emission, the United States have the highest emission in the BaU scenario of 21.5t per capita, which is 53% more than that in China and six-fold of that in France. In the 3°C grandfathering scenario, China and France have nearly the same level of emission per capita, which is 38% of that in the United States. In the 2°C grandfathering scenario, the per capita emission in the Unites States is 6t, which is 140% more than that in France and seven-fold of that in China. While under the Policy scenario, the per capita emission is the highest in China at 4t, nearly twice of that in the Unites States and three times of that in France. The details of per capita CO<sub>2</sub> emissions in 2050 of the three countries under the six scenarios can be found in the figure 3.15.



**Fig.3.15. Per capita CO<sub>2</sub> emissions by scenarios in 2050**

With the help of Sectoral Emission Model, we can have the technology roadmaps based on the presented CO<sub>2</sub> emission scenarios above for these three countries. The results will be shown in the following section.

## 3.4 Results for technology roadmaps

In this section, we will discuss different roadmaps under different criteria in achieving the governmental targets. As shown in the Sectoral Emission Model, the reduction of CO<sub>2</sub> emissions are decomposed into the reductions of sectoral CO<sub>2</sub> emissions, which means that the CO<sub>2</sub> reductions across sectors are substitutional. Thus, there will be infinite technology pathways in meeting the scenario objective. Most studies on the technology roadmaps are carried out by the minimum cost. However, the energy transition will not be influenced only by the costs, but also by energy policies, energy resources availability, etc. Under this consideration, we plan to present a solution pool of technology roadmaps only based on technology development.

The energy related technologies are: the share of coal and gas in the power sector<sup>23</sup>, the share of electric vehicles in the road transport and the improvement of energy efficiency in the residence and industry sector. Obviously, The share of coal and gas in the power sector are between 0 and 100%, with their sum inferior to 100%. The share of electric vehicles in all vehicles in the road transport is in the interval of [0%, 100%], and the improvement of energy efficiency in the residence and industry sector is in the interval of [0%, 100%)<sup>24</sup>.

In order to avoid the numberless solutions, we make the assumptions of the variables as following:

- The shares of electric vehicles are set from 0% to 100% with the interval of 20%;
- The improvements of energy efficiency in the residence and industry sector are set from 0% to 80% with the interval of 20%.

And then, we will discuss two technology roadmaps based on two criteria. One is based on the assumption that the technology development across sectors are developed homogeneously, the other is based on the preference of the most use of the energy sources of one country, which means to keep the change of energy mix in the power sector as little as possible.

The technologies involved in the technology roadmaps are the energy mix in the power sector, the share of electric vehicles used in the road transport, and the improvement of energy efficiency in the residence and industry sector in the three countries in 2050. In order to have a robust calculation, the sensitivities of parameters on the CO<sub>2</sub> emissions will be tested. The most important parameters in the Sectoral Emission Model are: CO<sub>2</sub> emission intensities of production for the three fossil fuels in 2050, the vehicle number in 2050, and the electricity output in 2050. The sensitivities of parameters will show the different importances of these parameters.

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<sup>23</sup> The share of oil is not presented in this section because its percentage is negligible compared to that of coal and gas, normally under 5%.

<sup>24</sup> The improvement of energy efficiency by 100% is not realistic as the emissions in the residence and industry cannot be eliminated perfectly.

### **3.4.1 Technology roadmaps for Policy scenario in China**

In this section, the technology roadmaps for the governmental target in China will be discussed. Firstly, we will present the solution pool of the technology roadmaps. Then we present the technology roadmaps with balanced technology development across sectors and the sensitivities of parameters under this technology roadmap. In the last part, we propose the technology roadmaps with least changed energy mix, and also present the sensitivities of parameters under this technology roadmap.

#### ***3.4.1.1 Technology solution pool for Policy scenario in China***

The Sectoral Emission Model propose a solution pool of the technology roadmaps for each country under all the CO<sub>2</sub> emission scenarios. In this section, we focus on the solution pool of technology roadmaps in 2050 for the Policy scenario.

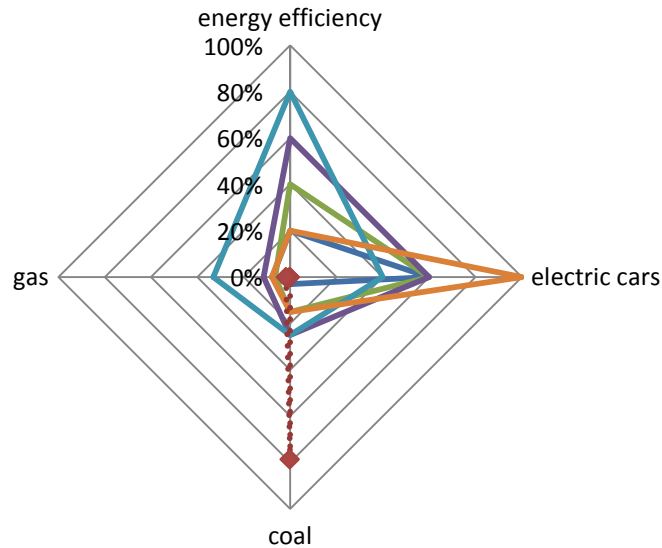
In China, half the CO<sub>2</sub> emissions from fuel combustion come from the power sector in 2010, with 78.7% electricity production from the combustion of coal. Thus, the reduction of emissions in the power sector is indispensable. The transport sector contributed only 7% of CO<sub>2</sub> emissions in 2050, but its reduction of emissions can not be ignored due to the rapid growth of car numbers.

According to the governmental target, the CO<sub>2</sub> intensity is projected to be reduced by 90% in 2050 with respect to 2005, which means that the CO<sub>2</sub> emissions will be reduced by 28% compared to the level in 2010. Different technology pathways are shown in the figure 3.16 without CCS and in the figure 3.17 with CCS, with the dotted lines representing the 2010 level.

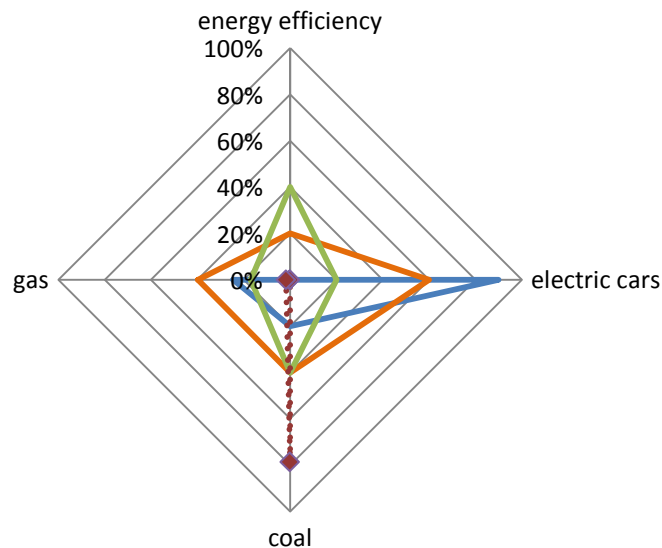
If CCS technology is not applied to the power plants, more efforts should be made in the transport sector and other sectors. For example, if the share of coal is to be reduced from 78.7% in 2010 to 25% in 2050, and the share of gas is to be increased from 1.7% to 33%, then 40% electric vehicles should be employed, and 80% energy efficiency should be improved. Otherwise, if 60% of vehicles are replaced by electric vehicles and the energy efficiency is improved by 20%, the power sector must be almost

decarbonized.

However, if all the power plants are equipped with CCS, when 60% of vehicles are replaced by electric vehicles and the energy efficiency is improved by 20%, the reduction of coal can be less than without CCS, from 78.7% to 40%, with the share of gas increased to 20%.



**Fig.3.16. Technology roadmaps for Policy scenario without CCS in China**



**Fig.3.17. Technology roadmaps for Policy scenario with CCS in China**

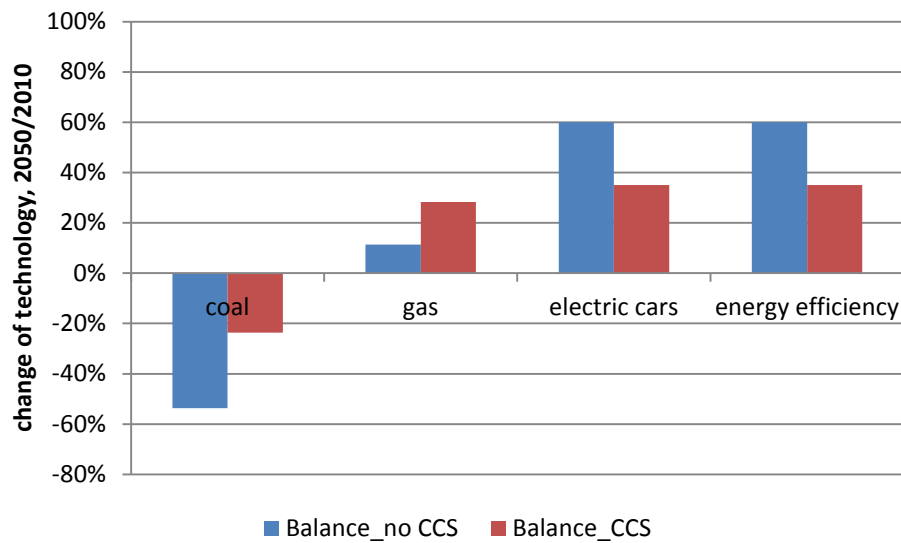
As the energy technologies in the three sectors are substitutional, there will be infinite possibilities for the technology roadmaps. Among the different technology

roadmaps in China in order to reach the governmental targets, we propose two roadmaps based on two criteria: one with balanced CO<sub>2</sub> emissions reduction across sectors, the other with least changed energy mix in the power sector. In each roadmap, the sensitivities of parameters: the CO<sub>2</sub> emission intensities of production of fossil fuels, the electricity output, and the number of vehicles, in the Sectoral Emission Model will be tested.

#### ***3.4.1.2 Balanced technology development roadmaps for China***

Under the balanced technology development criteria, the technologies across sectors are supposed to be developed homogenously. The figure 3.18 presents the roadmaps in this criterion with and without CCS for China in 2050. In order to achieve the governmental targets of reducing 90% of CO<sub>2</sub> intensity in 2050 with balanced technology development across sectors, electric vehicles in the road transport should replace 60% of the traditional automobiles. The energy efficiency in the residence and industry sector should be improved by 60%. Meantime, the share of coal used in the power generation is to be reduced by about 60%, from 78.7% to 25%, thus, the share of gas can be increased from 1.7% to 13% in 2050.

However, if the CCS technology is implemented in the power plants, there will be less direct CO<sub>2</sub> emissions reductions in the transport and other sectors. 35% of vehicles will be replaced by electric vehicles, and the energy efficiency in the residence and industry sector should be improved by 35%, nearly half less than the roadmaps without CCS. In the power sector, the coal combustion will be less reduced, from 78.7% to 55%, and the use of gas can be increased to 30% as gas is cleaner which produces less CO<sub>2</sub> emissions.



**Fig.3.18. Technology roadmaps for Policy scenario by balanced technology development in China in 2050 compared to 2010**

There are three most important parameters in the modeling: 1) the CO<sub>2</sub> emission intensities of production of fossil fuels, 2) the electricity output, and 3) the number of vehicles. Here, we will test their sensitivities in the two roadmaps above in order to make a robust simulation. The table 3.8 presents the influences by 1% diminution of the parameters on the total CO<sub>2</sub> emissions for the balanced technology development roadmap in China.

The sensitivities of the five parameters without CCS are more significant than those with the use of CCS. The electricity output has the most important sensitivities among these parameters with or without CCS, as the power sector contributes most to the total CO<sub>2</sub> emissions from fuel combustions. The second most important parameter is the CO<sub>2</sub> intensity of production of coal, because coal is the more used and more pollutant than oil and gas. The sensitivity of emission intensity of production of oil is the smallest, as the share of oil in the energy mix is negligible. The sensitivity of car number is very small, which is about 2% of that of electricity output.

**Tab.3.8. Sensitivity of parameters by balanced technology development on the CO<sub>2</sub> emissions in China**

$\Delta(-1\%)$	$e_{\text{coal}}$	$e_{\text{oil}}$	$e_{\text{gas}}$	Car number	Electricity output
<b>Balance_no CCS</b>	-0.3896%	-0.0025%	-0.0507%	-0.0106%	-0.4322%
<b>Balance_CCS</b>	-0.0849%	-0.0002%	-0.0116%	-0.0014%	-0.0953%

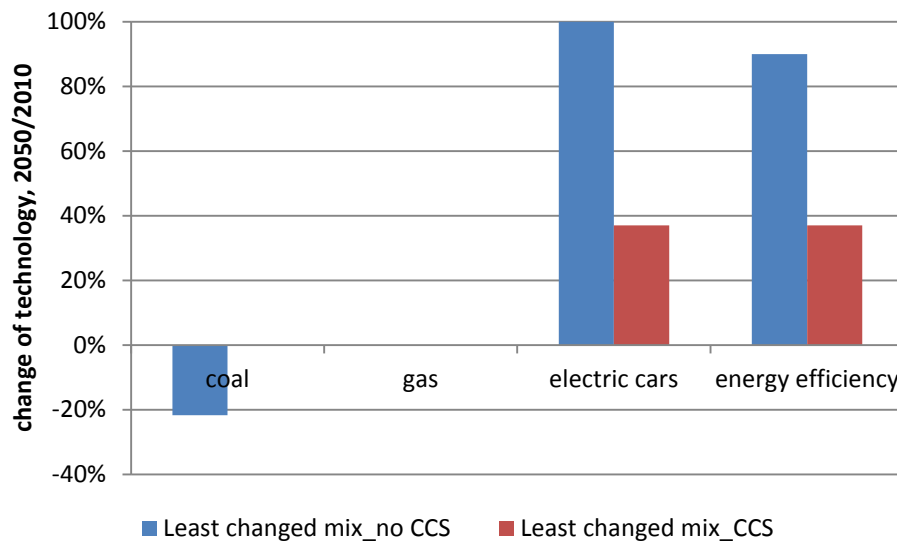
### **3.4.1.3 Least changed energy mix roadmaps for China**

In this section, we try to find out the technology roadmaps in changing the energy mix as little as possible, under the consideration of using their energy sources as much as possible. Thus, more efforts will be made in the transport and other sectors.

If CCS is not implemented, the coal in energy mix in the power generation in 2050 can not stay at the same level in 2010 even with the maximum effort of the two other sectors, as shown in the figure 3.19. Actually, if all cars are replaced by electric ones, and the energy efficiency is improved by 90% in the residence and industry, the share of coal will have to be reduced by 21.7% (from 78.7% to 57%), with the share of gas remained at 1.7%.

However, if all power plants are installed with CCS technology, it is possible that the energy mix stays at the same level in 2050. In the transport and other sectors, less reduction of CO<sub>2</sub> emissions are expected than with CCS. When there is no change in the energy mix in the power sector, 37% of cars have to be replaced by electric cars in the transport sector, and the energy efficiency in the residence and industry should be improved by 37%.





**Fig.3.19. Technology roadmaps for Policy scenario by least changed energy mix in China in 2050 compared to 2010**

As to the sensitivities of parameters, the electricity output and the emission intensity of coal have nearly the same sensitivities with or without CCS. Meanwhile, they have the most important sensitivities on the CO<sub>2</sub> emissions, as shown in the table 3.9. The second most important sensitivity is that of the car number, but only 4% of the sensitivity for electricity output when CCS is used and 1.5% when CCS is not used. The sensitivities of emission intensity of production of gas and of oil are negligible compared to those of electricity output.

**Tab.3.9. Sensitivity of parameters by least changed energy mix on the CO<sub>2</sub> emissions in China**

$\Delta(-1\%)$	$e_{\text{coal}}$	$e_{\text{oil}}$	$e_{\text{gas}}$	Car number	Electricity output
Least changed energy mix_no CCS	-0.9025%	-0.0032%	-0.0067%	-0.0358%	-0.8766%
Least changed energy mix_CCS	-0.1215%	-0.0002%	-0.0007%	-0.0018%	-0.1206%

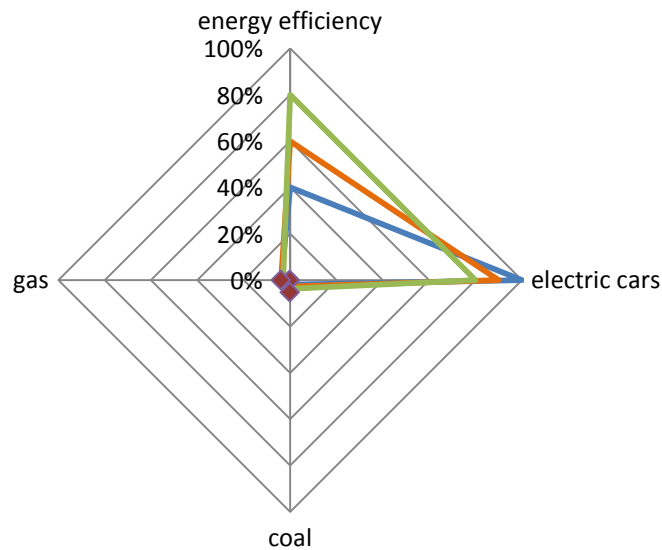
In brief, the governmental target of reducing CO<sub>2</sub> emissions in 2050 are relatively tolerant, nearly four times of the objective of the 2°C equal emission scenario. There are all kinds of technology roadmaps for the Policy scenario. If the energy mix is planned to stay at the same level in 2010, the CCS must be used in the power plant. Otherwise, the transport sector and other sectors should make enormous efforts in reducing direct CO<sub>2</sub>

emissions. The emission intensity of production of coal and the electricity are the two parameters with most important sensitivity on the CO<sub>2</sub> emissions, for both the balanced technology development roadmap and the least changed energy mix roadmap.

### **3.4.2 Technology roadmaps for Policy scenario in France**

In France, nearly 80% of the electricity is produced by nuclear power. The CO<sub>2</sub> emissions from the power sector account for 15% of the total emissions in 2010. The shares of the coal, oil and gas are less than 5% respectively. Thus, in the technology roadmaps for France, we focus on the transport and other sectors since the majority of efforts must be supported by these sectors. CCS is not a prior option for France as the CCS is principally installed with the power plants. Different from the other two country, the technology roadmaps in France will not consider the implementation of CCS.

In the Policy scenario, the CO<sub>2</sub> emissions in 2050 are planned to be reduced to 25% of the level in 2010. The transport sector is still the most important sector in the contributions to the emission reductions. The technology pathways are presented in the figure 3.20. The energy efficiency in the residence and industry should be improved by at least 40%, and at least 80% of vehicles should be replaced by the electric vehicles. For example, if the energy efficiency is improved by 80%, 80% of vehicles should be changed to electric vehicles to reach the governmental target. If all the vehicles are replaced by electric vehicles, the energy efficiency is expected to be improved by 40%.

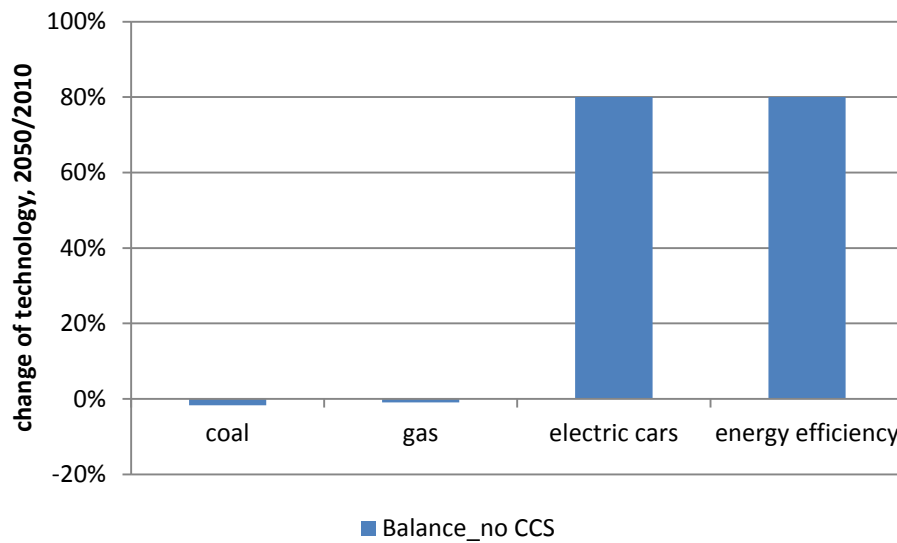


**Fig.3.20. Technology roadmaps for Policy scenario without CCS in France**

As in France, the share of coal and gas are very small, the power sector will not contribute much to the CO<sub>2</sub> emission reductions. Actually, the roadmaps with the balanced technology development and the least energy mix are basically the same. Thus here we only discuss the balanced technology development roadmaps. Then we will present the sensitivities of parameters: the CO<sub>2</sub> emission intensities of production of fossil fuels, the electricity output, the number of vehicles in the Sectoral Emission Model.

### ***3.4.2.1 Balanced technology development roadmaps for France***

In France, as the share of coal, oil, and gas are already all less than 5%, the power sector can not make much contribution to the reduction of emissions. Most CO<sub>2</sub> emissions will be reduced in the power sector and other sectors. In the figure 3.21, we can see that in order to reach the governmental target, 80% of the cars should be replaced by electric cars and the energy efficiency is to be increased by 80%. In this condition, the share of coal should be reduced by 1.7%, from 5.3% to 3.5, and the share of gas by 0.9%, from 3.9% to 3%.



**Fig.3.21. Technology roadmaps for Policy scenario by balanced technology development in France in 2050 compared to 2010**

The sensitivities of parameters in the roadmap above are presented in the table 3.10. Although most of reductions are carried out in the transport sector and the other sectors, the electricity output has the most important sensitivity. The second important sensitivity is that of the emission intensity of production of coal, because coal has the highest emission level. The car number has the smallest sensitivities among all the parameters, which is only 7% of that of electricity output.

**Tab.3.10. Sensitivity of parameters by balanced technology development on the CO<sub>2</sub> emissions in France**

$\Delta(-1\%)$	$e_{\text{coal}}$	$e_{\text{oil}}$	$e_{\text{gas}}$	Car number	Electricity output
Balance_no CCS	-0.1889%	-0.0315%	-0.0394%	-0.0163%	-0.2435%

In brief, the CCS is not a necessary option for the energy roadmaps since the fossil fuels are barely used in the power sector. The governmental target in 2050 is very severe, nearly the same level of the 2°C equal emission scenario. In order to achieve this objective, the transport sector and the other sectors should make large contributions, especially the transport sector. Under the assumption that the technologies are developed evenly across sector, 80% of electric vehicles should be used, and the energy efficiency should be improved by 80% compared to the 2010 level. However, the

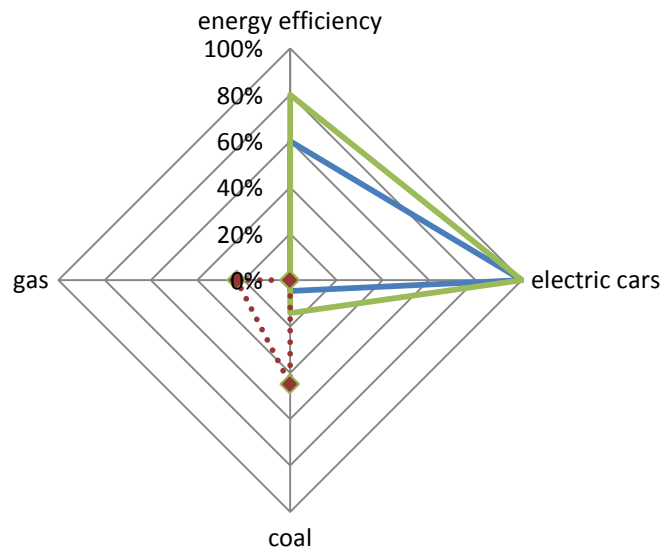
electricity output and emission intensity of production of coal have the most important sensitivity on the CO<sub>2</sub> emissions even though the share of coal in the energy mix is very small.

### **3.4.3 Technology roadmaps for Policy scenario in the United States**

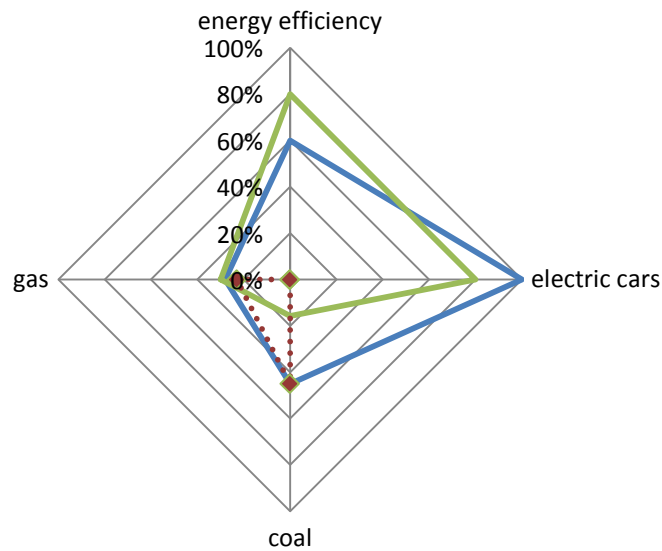
In the United States, 43% of the CO<sub>2</sub> emissions come from the power sector in 2010, with the share of coal used in the power sector at 45%, and the share of gas at 23%. The second largest source of emissions was the transport sector, accounting for 30% of total CO<sub>2</sub> emissions in 2010.

According to the government policy, the CO<sub>2</sub> emissions will be reduced by 82% compared to 2010 level. Its technology pathways in the policy scenario are shown in the figure 3.22 without CCS and in the figure 3.23 with CCS. In order to achieve this objective, all the electric vehicles should be replaced by electric vehicles if no CCS is applied. In this case, either the energy efficiency is improved by 60% and the power sector should be nearly decarbonized, or the energy efficiency is to be improved by 80% and the share of coal is to be reduced at 14%.

If CCS is implemented with all power plants, when the energy efficiency is improved by 60% and all vehicles are replaced by electric vehicles, the share of coal can be kept at 45% with the share of gas at 28%. When the energy efficiency is improved by 80%, and 80% of vehicles are changed to electric vehicles, the share of coal is to be reduced to 16% with the share of gas at 30%.



**Fig.3.22. Technology roadmaps for Policy scenario without CCS in the US**



**Fig.3.23. Technology roadmaps for Policy scenario with CCS in the US**

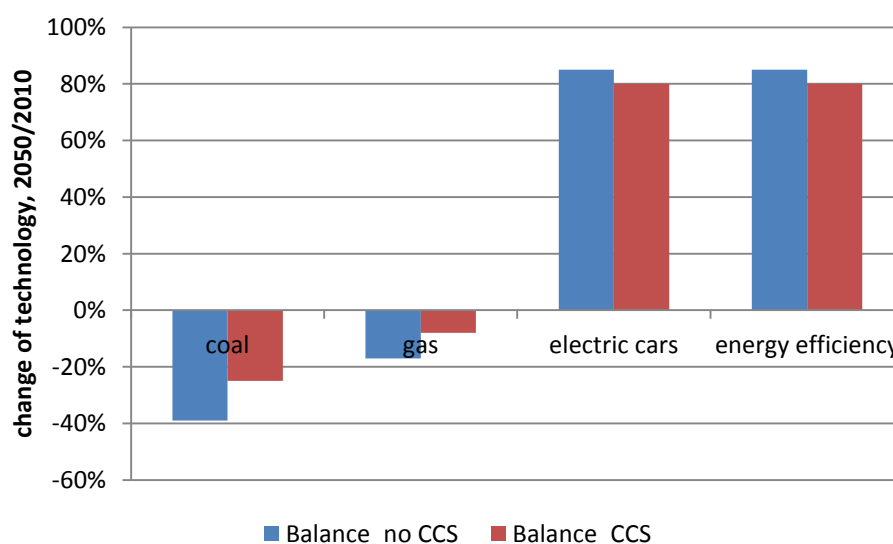
Among the different technology roadmaps in the United States in order to reach the governmental targets, the roadmaps based on two criteria: one with balanced CO<sub>2</sub> emissions reduction across sectors, the other with least changed energy mix in the power sector are presented in the following sub-section. Same as in the previous two sub-sections, the sensitivities of parameters in the Sectoral Emission Model for each roadmap will be tested.

### 3.4.3.1 *Balanced technology development roadmaps for the United States*

In the United States, the power sector and transport sector are two most important sectors for CO<sub>2</sub> emissions, which account for respectively 43% and 30% of total emissions in 2010.

The figure 3.24 show the technology roadmaps for Policy scenario with balanced technology development across sectors with and without CCS. If CCS is not considered in the energy transition in the United States, 85% of vehicles should be replaced by electric vehicles, and the energy efficiency in the residence and industry sector should be improved by 85%. In the power sector, the share of coal will be reduced by 39%, from 45% to 6%, and the share of gas should be reduced by 17%, from 23% to 6%.

If CCS is implemented in all power plants, the direct reduction of emissions should be slightly less than that without CCS: 80% of cars should be replaced by electric cars, and the energy efficiency should be improved by 80%. Meanwhile, more fossil fuels can be used in the power sector than without CCS. The share of coal should be reduced by 25%, from 45% to 20%, and the share of gas should be reduced by 8%, from 23% to 15%.



**Fig.3.24. Technology roadmaps for Policy scenario by balanced technology development in the US in 2050 compared to 2010**

The sensitivities of parameters are shown in the table 3.11. Electricity output has the most important sensitivity among all parameters, with or without CCS. The emission intensity of production of coal has the second most important sensitivity, about 80% of the sensitivity of electricity output. The sensitivity of emission intensity of production of gas is 25% of the sensibility of emission intensity of production of gas without CCS, and 18% with CCS. The sensitivity of emission intensity of production is the smallest among the three fuels because it has the least share in the energy mix. The car number has the least sensitivity, at about 5% of the sensitivity of the electricity output.

**Tab.3.11. Sensitivity of parameters by balanced technology development on the CO<sub>2</sub> emissions in the US**

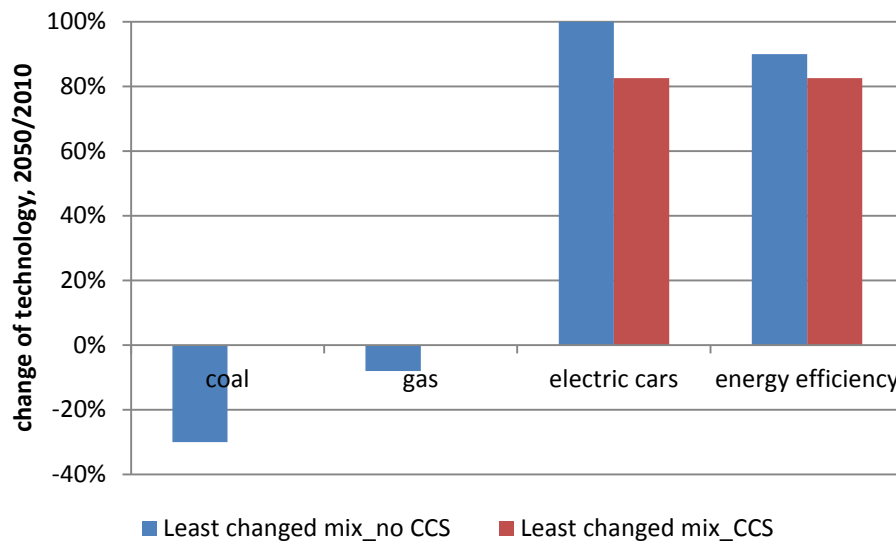
$\Delta(-1\%)$	$e_{\text{coal}}$	$e_{\text{oil}}$	$e_{\text{gas}}$	Car number	Electricity output
<b>Balance_no CCS</b>	-0.2468%	-0.0206%	-0.0617%	-0.0159%	-0.3131%
<b>Balance_CCS</b>	-0.0820%	-0.0021%	-0.0154%	-0.0045%	-0.0949%

### ***3.4.3.2 Least changed energy mix roadmaps in the United States***

The technology roadmaps with the least change of energy mix are shown in the figure 3.25. When CCS is not implemented, all vehicles should be replaced by electric vehicles, and energy efficiency in the residence and industry sector should be improved by 90%. Even with the large reduction in the transport and other sectors, the energy mix in the power sector can not stay the same level as in 2010. In the power sector, the share of coal will be reduced by 30%, from 45% to 15%, and the share of gas will be reduced by 8%, from 23% to 15%.

If CCS is implemented in all power plants, it is possible that the energy mix in the power sector stay unchanged. Under this condition, 82.5% of cars should be replaced by electric cars, and the energy efficiency should be improved by 82.5%.





**Fig.3.25. Technology roadmaps for Policy scenario by least changed energy mix in the US in 2050 compared to 2010**

The sensitivities of parameters in the technology roadmaps by least changed energy mix are shown in the table 3.12. Electricity output has the most important sensitivity among all parameters, with or without CCS. The emission intensity of production of coal has the second most important sensitivity, about 82% of the sensitivity of electricity output without CCS and 92% with CCS. The sensitivity of emission intensity of production of gas is 21% of the sensibility of emission intensity of production of gas without CCS, and 11% with CCS. The sensitivity of emission intensity of production is the has the least sensitivity since it has the least share in the energy mix. The sensitivity of car number is at about 5% of the sensitivity of the electricity output.

**Tab.3.12. Sensitivity of parameters by least changed energy mix on the CO<sub>2</sub> emissions in the US**

$\Delta(-1\%)$	$e_{\text{coal}}$	$e_{\text{oil}}$	$e_{\text{gas}}$	Car number	Electricity output
Source max_no CCS	-0.6222%	-0.0207%	-0.1555%	-0.0451%	-0.7534%
Source max_CCS	-0.1848%	-0.0021%	-0.0236%	-0.0099%	-0.2006%

In brief, the governmental target of reducing CO<sub>2</sub> emissions is very severe, twice of that in the 2°C equal emission scenario. In order to achieve this objective, all sectors should make large emission reductions. If the energy mix is expected to be kept at the

same level in 2010, the CCS should be implemented in all power plants. If the CCS is not used, it is impossible to keep the energy mix unchanged even though the other sectors all make maximum efforts. Same as China and France, the electricity output and the emission intensity of production of coal have the most important sensitivities on the CO<sub>2</sub> emissions.

## 3.5 Conclusion and discussion

In response to the climate change, many countries have promised reduction targets for CO<sub>2</sub> emissions up to 2050, which reflected their own particular situations, mainly regarding population changes, economic growth and technological developments. In this chapter, a Sectoral Emission Model has been set up for CO<sub>2</sub> emissions between 2010 and 2050 in China, France and the United States, with several CO<sub>2</sub> emission scenarios and the governments targets.

This model was proposed in order to give technology roadmaps for both the governmental targets and the climatic objectives of the scientific community, and also to provide the policy makers and civil societies a clearer insight of the problem in order to better choose their technology pathways for reducing emissions according to their own criterion.

Apart from the BaU scenario as the reference scenario, and also the scenarios of governmental targets, we set up two approaches for the 2°C and 3°C scenarios: grandfathering and equal emission convergence, under the consideration of different economy development and different emission levels. All the government policy proved to be more tolerant than the 2°C equal emission scenario, but more severe than the 2°C grandfathering scenario (except for China). Hitting governmental targets would require huge improvements in many aspects without the advanced technology, such as CCS. In China, the 2°C grandfathering scenario, and 3°C and 2°C equal emission scenarios, prove stricter than the Policy scenario. The model shows that it will need completely change of energy structure in all sectors under current technologies to achieve these

scenarios:

- In China, half of the emission reductions are expected to be contributed by the power sector, as the power sector accounts for half the emissions in 2010. In the 2°C grandfathering scenario and 2°C equal emission scenario, China is obliged to decarbonize at the maximum level in all the sectors in 2050. While in the Policy scenario (which is more tolerant), 60% of vehicles should be replaced by electric vehicles, energy efficiency should be improved by 60%, and coal utilization should be reduced by 60%. If the energy mix is expected to be kept unchanged, then CCS should be implemented.
- In France, two thirds of emission reductions are expected to be contributed by the transport sector. 80% of vehicles should be changed into electric vehicles for the 2°C equal emission scenario and Policy scenarios. Meanwhile, the energy efficiency should also be improved by 80% to reach the governmental target. As the power sector contributes little to the CO<sub>2</sub> emission, CCS is not a necessary option for France.
- In the United States, the reduction of emissions is divided homogeneously across sectors as all the three sectors have the same importance for the reduction of emissions. The 2°C equal emission scenario is very strict, in which all the sectors must be decarbonized at maximum (about 90% of emissions in each sector should be reduced). And in the Policy scenario, all sectors should make large effort (more than 80% of emissions should be reduced) in order to reduce CO<sub>2</sub> emissions. Same as China, if the energy mix is expected to be kept unchanged, then CCS should be implemented.

The test of sensitivities of parameters in our Sectoral Emission Model for different technology roadmaps, in different countries, show that the electricity output and the emission intensity of production are the two parameters with the most important sensitivity on CO<sub>2</sub> emissions. Thus, improving the efficiency of coal combustion will play an important role in the emission reductions.

Now we would like to mention a few perspectives of research which are worth exploring in the future. Firstly, it could be worth presenting alternative ways for the choice of a technology roadmap among the solutions found by our model, which means, for example, with the use and help of other criteria, such as minimization of global investment costs of energy mix.

The choice of a technology roadmap is a complex issue. The dimensions of the problem are multiple and the question of energy prices (which is central) is not the only one to take into account. These include issues related to the security of the local population and those related to security of supply of fuels, etc. Having made these remarks, we could easily add new parameters with our flexible model, e.g.:

- As many uncertainties weigh on prices of resources in the future (the uncertainties are all resources now), we defend the idea of adding new scenarios of prices of fuels;
- In future works, more energy related technologies should be added to this model, with new scenarios of development/improvement of technologies (we took into account the CCS, and one can also think of the possible generation 4 of nuclear reactors, etc.).

Thus, with the comparison of the technology pathways among the three countries, we could better see the technologies advancement and change they should make to achieve the global objectives or their own targets.

Finally, it would be interesting to add new social factors in this model. Here is the biggest uncertainty for new perspectives of research: how to introduce it in the current model? These questions go from:

- The preference theory: with the utility function consisting of assessments of consumers about the risks and issues of security. Actually preferences are totally absent in our model;
- To public economics theories of externalities: with the literature on the monetary valuation of negative externalities of pollution for example (see European project NEEDS in particular (Neij et al., 2006)), one could imagine that the prices of fuels would be reviewed by the amount of the

negative externalities that are linked to CO<sub>2</sub> emissions of each technology.

These are a few possible questions for further research. The next chapter addresses the question of inequality in emissions of CO<sub>2</sub> among countries: The differences in per capita CO<sub>2</sub> emissions among countries show different contributions to climate change, and thus the emissions distribution has become a central issue in dealing with the negotiation and agreement for global climate change.

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# Chapter 4

## Optimization of sector per capita CO<sub>2</sub> emissions equity on three Countries: China, France and the US, over the period 2010-2050

### 4.1 Introduction

As mandated by the UN Framework convention on Climate Change (UNFCCC), stabilization of Greenhouse Gas (GHG) emissions concentrations implies establishing limits to the level of global emissions and distributing this level among the different countries. These limitations might involve economic sacrifices, as CO<sub>2</sub> emission is an undesired sub-product of economic activity (Duro and Padilla, 2008).

Besides, there are strong differences in the level of GHG emissions caused by the inhabitants of different parts of the world. The differences in per capita CO<sub>2</sub> emissions among countries show different historic responsibilities in the GHG generation and then contribute to climate change. Thus, the countries' emissions distribution has become an important issue in dealing with the negotiation and agreement of policies for global climate change.

Many studies have been carried out for the fairness of responsibilities in terms of

CO<sub>2</sub> emission distributions in the national level (Dellink et al., 2009; Gupta and Bhandari, 1999; Heyward, 2007; Höhne et al., 2013; Philibert and Pershing, 2001; Raupach et al., 2014; Ringius et al., 2002; Roberts, 2001; Yedla and Garg, 2014). Most of these studies first define a global level of CO<sub>2</sub> emissions in a certain year or period, which is consistent with meeting a long-term climate objective (e.g. 400-450 ppm CO<sub>2</sub>e, equivalent to 2 degrees increase of global temperature). Then they apply rules or criteria to allocate efforts to countries or regions with the aim of meeting the global emissions level. Each study made different assumptions about the global emissions pathway, the specific national efforts required, the equity principles, and other variables (Den Elzen and Höhne, 2008).

The carbon equity issues are mostly discussed on the international negotiations for the carbon allocation budget. However, in the international climate change negotiations, they have to consider the level of action that each country would need to undertake to achieve the objective of limiting the temperature increase under security level in applying the carbon equity principles. These literatures did not point out how to apply the equity principles on the level of action that each country would need to undertake. In this chapter, we will try to find energy roadmaps in applying the equity principles into different energy sectors.

Actually, with the globalization and the potential of technology development in the worldwide, there could be a real convergence of technologies in each energy sector. This is a scenario that we think quite possible, as shown in the following studies (Cornell et al., 2012; Da Costa and Shoai Tehrani, 2013; Finon and Perez, 2008; Mosseri and Jeandel, 2013; Zaccai et al., 2012).

It is this scenario that will be studied in details in this Chapter 4. Under this assumption we propose an optimization method to minimize the per capita emissions inequality across main energy sectors, which are power sector, transport sector, and other sectors, among three countries: China, France and the United States. In this chapter, the Theil index is chosen to be the measurement of inequality of per capita CO<sub>2</sub> emissions. Then the Differential Evolution methodology is used to carry out the carbon equity optimization with multiple objectives.

The optimization of sector per capita emissions equity is based on the Sectoral

Emission Model built and exploited in Chapter 3. We aim to find the technology pathways in the context of realizing the best equity of per capita emissions across sectors under certain emissions scenarios, by introducing a benchmark nation: here is France. Why do we choose France as benchmark country?

First of all, because the per capita emissions level is relatively low in France compared to the worldwide level. Besides, its per capita emission in the power sector is low, relative to that in the US and in China. Then we hope to find pathways by converging the per capita emissions for the most two important emitters: China and the United States, to France, in different scenarios.

In addition, the 3°C and 2°C scenarios with grandfathering and equal emission allocation methods are set to be the reference scenarios for the Policy scenario. The energy roadmap for achieving the governmental targets will be proposed through optimization, and then we will test the sensitivity of parameters in our Sectoral Emission Model for this energy roadmap in Policy scenario.

As expected, the first results show that the inequality of per capita sectoral CO<sub>2</sub> emissions in the Policy scenario is higher than the 3°C and 2°C equal emission scenario, but it is lower than the 3°C and 2°C grandfathering scenario. We find that: in order to achieve the governmental target, two third of coal combustion should be reduced in China, and the coal should be almost eliminated in the United States. However, gas is encouraged to be used in the power sector, especially in the United States. As to the transport sector, more than 60% of vehicles should be replaced by electric vehicles in China, and this share will be about 90% in France and the United States. In the residence and industry sector, the energy efficiency should be improved by about 50% in China and France, 70% in the United States.

As to the sensitivities of parameters in the model, the most important parameter proves to be the electricity output parameter for all the three countries. The CO<sub>2</sub> emission intensity of production of coal in China and that of gas in the United States also play an important role in influencing the CO<sub>2</sub> emissions. Because large percentages of vehicles are expected to be changed to electric vehicles in these countries, the parameters in the power sector become more important to obtain the governmental reduction targets in reducing the sectoral carbon inequality.

The remainder of this chapter is organized as follows:

- Section 2 will introduce the optimization method and inequality index.
- In section 3, the results of the multi-objective optimization will be presented.
- And section 4 concludes the work.

## 4.2 Optimization methodology

In this section, we will introduce inequality index to measure the per capita emissions inequalities, and the optimization method in order to minimize the inequality per capita emissions across sectors.

The per capita sectoral emission inequality of all CO<sub>2</sub> emission scenarios in Chapter 3 (3°C grandfathering scenario, 3°C equal emission scenario, 2°C grandfathering scenario, 2°C equal emission scenario, and Policy scenario) will be optimized. This optimization is based on the Sectoral Emission Model, which is carried on for China, France and the United States, under consideration of different situations in these countries. Then, we will discuss the technology roadmaps in the Policy scenario, in comparison with other scenarios.

The carbon inequality index will be firstly presented in this section.

Then the optimization method, named Differential Evolution method, will be introduced.

## 4.2.1 Carbon inequality index

The essence of carbon inequality is to measure the differences of each emission allocation plans (Teng et al., 2011). In the literature on the climate change, there have been several attempts to use the tools of income distributive analysis to measure inequality in CO<sub>2</sub> emissions and CO<sub>2</sub> intensities across countries and its development over time (Groot, 2009):

- Hedenus and Azar (2005) measured emission inequality across countries by the absolute and relative gap between the top and bottom quintile per capita carbon emitters and by the well-known Atkinson index over the interval 1961-1999.
- Heil and Wodon (1997) used the Gini index to measure the inequality of emission across countries from 1960 to 1990.
- Heil and Wodon (2000) have also employed Gini index to conduct a study of perspective inequality to 2100, by considering the relative scenarios and Kyoto Protocol and other reduction measures.
- Duro and Padilla (2006) applied the decomposable Theil index of inequality to emissions to study the driving forces in terms of Kaya factors.
- Clarke-Sather and Qu (2011) compared the carbon inequality on a sub-national level in China between 1997 and 2007 using several measures: Gini index, Theil index, Kakwani index and coefficient of variation (CV).
- Padilla and Duro (2013) analyzed the inequality of per capita CO<sub>2</sub> emissions in the European Union with Theil index for the period 1990-2009.

We have proposed to study the inequality of per capita emissions in the European Union in the baseline scenario and burden sharing scenario between 1990 and 2010 with Gini coefficient (Tian and Da Costa (2014a)).

Among all the inequality indices above, Gini index and Theil index are two most widely used indices in representing inequality terms. Gini proposed the equality level measurement defined as a ratio of the areas on the Lorenz curve diagram. Gini index is easy to be interpreted, the smaller the area between the perfect equality curve and the Lorenz curve, the smaller inequality is. Gini index is a positive number between 0 and 1, with 0 the perfect equal allocations and 1 the perfect unequal allocations. According to the United Nation's definition, Gini index inferior to 0.2 corresponds to perfect income equality, 0.2 to 0.3 corresponds to relative equality, 0.3 to 0.4 corresponds to adequate equality, 0.4 to 0.5 corresponds to big income gap, and superior to 0.5 corresponds to severe income gap. Despite of its advantages, it is not the most appropriate index in the optimization. In fact, Gini index is proposed as a graphic definition, thus it is difficult to present it in a simple mathematical formulation.

Thus, in this work, we adopt the Theil index for the reason that it can be easily presented by equations which will facilitate the calculation. Even though there are not standard criteria for Theil index in depicting the inequality level, it is obvious that the smaller the absolute value of Theil index, the smaller the inequality is. The relative inequality level can be observed in comparing the Theil index for different groups.

The Theil index of per capita CO<sub>2</sub> emissions is presented in the following equation:

$$T(c, p) = \sum_i p_i * \ln\left(\frac{\bar{c}}{c_i}\right) \quad (12)$$

where  $p_i$  is the share of population for the country  $i$  in the total population,  $c_i$  is the per capita emission of country  $i$ ,  $\bar{c}$  is the mean per capita emission of countries.

Thus, the Theil index of sector per capita CO<sub>2</sub> emissions can be presented in the equations 13 to 15:

- 1) Theil index of per capita CO<sub>2</sub> emissions in the power sector:

$$\sum p_i * \ln(\bar{c}_{\text{power}}/c_{i,\text{power}}) \quad (13)$$

- 2) Theil index of per capita CO<sub>2</sub> emissions in the transport sector:

$$\sum p_i * \ln(\bar{c}_{\text{transport}}/c_{i,\text{transport}}) \quad (14)$$

- 3) Theil index of per capita CO<sub>2</sub> emissions in the other sectors:

$$\sum p_i * \ln(\bar{c}_{\text{other}}/c_{i,\text{other}}) \quad (15)$$

where  $c_{i,sector}$  is the per capita emissions in the corresponding sector for the country  $i$ ,  $\bar{c}_{sector}$  is the mean per capita emission in the corresponding sector of countries.

### ➤ Constraint equations:

We employ the equations in the Sectoral Emission Model in Chapter 3. The optimization is carried out for each scenario with the same parameters and variables in model.

The first constraint equation is set for each scenario as following:

$$\begin{aligned}
 & \text{Total emissions}_{scenario,i} \\
 & = (\text{electricity output}_{2050,i} + 0.73 * y_i * N_{2050,i}) * (x_{coal} * e_{coal} + x_{oil} * e_{oil} + x_{gas} * e_{gas}) \\
 & + \text{Transport emissions}_{2050,i} * (1 - y_i) + \text{Other emissions}_{2050,i} * (1 - e_i) \quad (16)
 \end{aligned}$$

It is obvious that all the variables  $\in [0,1]$ , because all the variables are set to be shares. Besides, the sum of the energy mix should be inferior to 1. Thus, the second constraint equations are:

$$\begin{aligned}
 0 & \leq y_i \leq 1 \\
 0 & \leq e_i \leq 1 \\
 (x_{coal} + x_{oil} + x_{gas})_i & \leq 1 \quad (17)
 \end{aligned}$$

In the optimization, the energy mix among France, China and the United States will converge for each fuel in order to get the minimization of per capita emissions. But, the fossil fuels are barely used in the electricity production in France, with the share of each fuel under 5% in 2010. Thus, it is not expected that the use of fossil fuels will increase in the power sector. In this context, we assume that the energy mix in France in 2050 will not be superior to the 2010 level under the current policy.

Thus the third constraint equation is:

$$(x_{coal}, x_{oil}, x_{gas})_{2050,FR} \leq (x_{coal}, x_{oil}, x_{gas})_{2010,FR} \quad (18)$$



### ➤ Objective equations:

In the optimization, our objective is to minimize the inequalities of per capita CO<sub>2</sub> emissions by sectors. So we set up the first optimization function which minimizes the sum of the squares of sector Theil index. The square is used in order to avoid the offset of values of Theil index which is  $\in (-\infty, +\infty)$ .

The first objective equation is:

$$\min \left\{ \left[ \sum p_i * \ln \left( \frac{\bar{c}_{power}}{c_{i,power}} \right) \right]^2 + \left[ \sum p_i * \ln \left( \frac{\bar{c}_{transport}}{c_{i,transport}} \right) \right]^2 + \left[ \sum p_i * \ln \left( \frac{\bar{c}_{rest}}{c_{i,rest}} \right) \right]^2 \right\} \quad (19)$$

In China, France and the United States, the energy mix is different from each other, because of different natural resources reserves, energy policies, etc. Under the consideration of these different energy structures, we propose the second objective equation which means to minimize the differences of the energy mix in 2050 compared to 2010 level:

$$\min [\sum (x_i - x_{2010})^2] \quad (20)$$

## 4.2.2 Differential evolution methodology

Along with Theil index, the Differential Evolution (DE) method is adopted in the Sectoral Emission Model in order to optimize the per capita CO<sub>2</sub> emissions inequalities across sectors among China, France and the United States.

The Differential Evolution method is used in this work because it is a widely used optimization method for continuous variables in the non-linear equation oriented models (Storn and Price, 1997). This method is firstly used in the applied mathematics and computation, and then it is applied in the energy system engineering. Wang et al. (2013) used this method for a multi-objective optimization of large-scale coal-fired power plants. Khademi et al. (2010) applied the DE method to optimize a novel reactor composed with the hydrogen production, cyclohexane dehydrogenation and methanol synthesis in considering the mole fractions of methanol, benzene and hydrogen in permeation side as the main objectives. Glotic et al. (2014) used it to optimize the water

quantity uses per electrical energy produced in the hydro power plants. It is a metaheuristic method which can be easily applied to experimental minimization with good convergence properties. The advantage of this method is that it is self-organizing so that very little input is required from the user.

The DE method utilizes NP D-dimensional parameter vectors

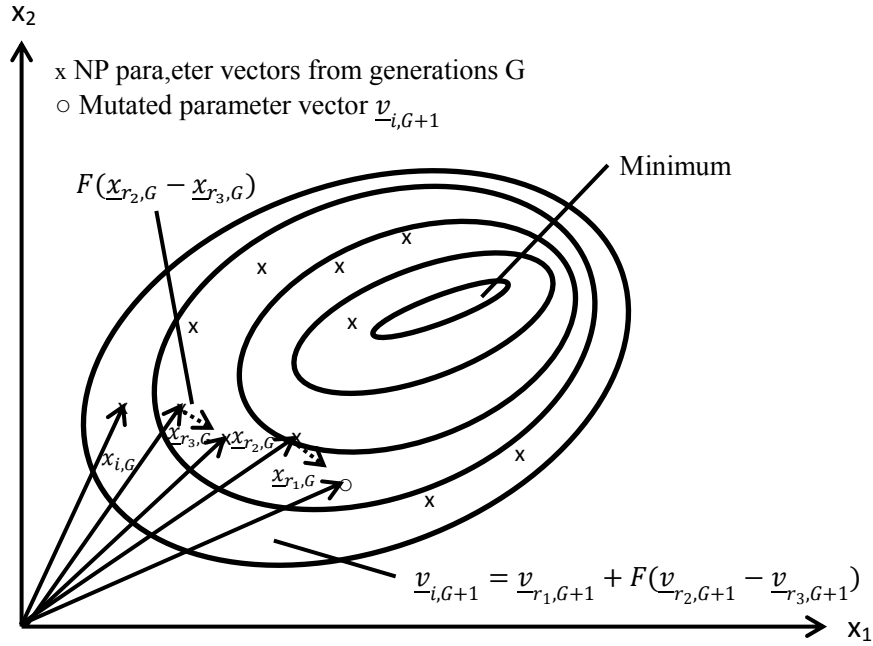
$$x_{i,G}, i = 1, 2, \dots, NP \quad (21)$$

as a population for each generation G. The initial vector population is chosen randomly. And after the mutation, which means to generate new parameter vectors by adding the weighted difference between two population vectors to a third vector, the mutated vector's parameters are then mixed with the parameters of another predetermined vectors, so-called crossover.

For each target vector,  $x_{i,G}, i = 1, 2, \dots, NP$ , a mutant vector is generated according to :

$$v_{i,G+1} = x_{r_1,G} + F * (x_{r_2,G} - x_{r_3,G}) \quad (22)$$

with random indices  $r_1, r_2, r_3 \in \{1, 2, \dots, NP\}$ , integer, mutually different and  $F > 0$ . The randomly chosen integers  $r_1, r_2$  and  $r_3$  are also chosen to be different from the running index  $i$ , so that NP must be greater or equal to four to allow for this condition. F is a real and constant factor  $\in [0, 2]$  which controls the amplification of the differential variation  $(x_{r_2,G} - x_{r_3,G})$ . The figure 4.1 shows a two-dimensional example that illustrates the different vectors which play a part in the generation of  $v_{i,G+1}$ .



**Fig.4.1. Two-dimension objective function with its contour lines and the process for generating  $v_{i,G+1}$  (Storn and Price, 1997)**

In order to increase the diversity of the perturbed parameter vectors, the trial vector is introduced by crossover:

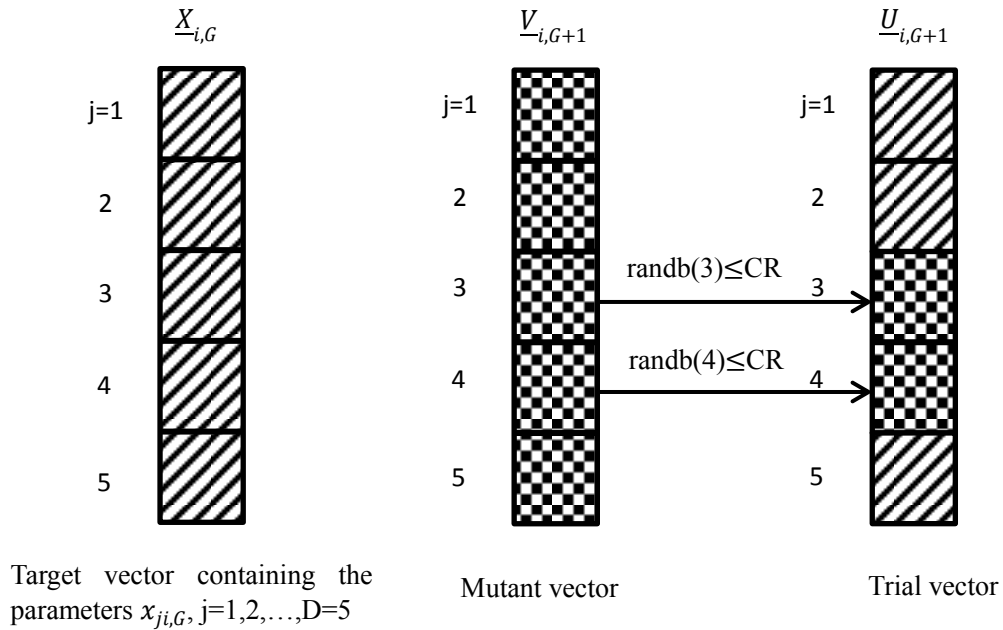
$$u_{i,G+1} = (u_{1i,G+1}, u_{2i,G+1}, \dots, u_{Di,G+1}) \quad (23)$$

with:

$$u_{ji,G+1} = \begin{cases} u_{ji,G+1} & \text{if } (randb(j) \leq CR) \text{ or } j = rnbr(i) \\ u_{ji,G} & \text{if } (randb(j) > CR) \text{ and } j \neq rnbr(i) \end{cases}$$

$$j = 1, 2, \dots, D. \quad (24)$$

where the  $randb(j)$  is the  $j^{\text{th}}$  evaluation of a uniform random number generator with outcome  $\in [0,1]$ . CR is the crossover constant  $\in [0,1]$  which has to be determined by the user.  $rnbr(i)$  is a randomly chosen index  $\in 1, 2, \dots, D$  which ensures that  $u_{i,G+1}$  gets at least one parameter from  $v_{i,G+1}$ . The figure 4.2 gives an example of the crossover mechanism for 5-dimensional vectors.



**Fig.4.2. Illustration of the crossover process for  $D=5$  parameters (Storn and Price, 1997)**

To decide whether or not it should become a member of generation  $G+1$ , the trial vector  $u_{i,G+1}$  is compared to the target vector  $x_{i,G}$  using the greedy criterion. If vector  $u_{i,G+1}$  yields a smaller cost function value than  $x_{i,G}$ , then  $x_{i,G+1}$  is set to  $u_{i,G+1}$ ; otherwise, the old value  $x_{i,G}$  is retained.

Here in our optimization, we have in total 15 dimensions, which are  $(x_{\text{coal}}, x_{\text{oil}}, x_{\text{gas}}, y, e)_i$ ,  $i = \text{CN, FR, US}$ . And the NP is set to be 50 after trials.

The results of the multi-objective optimization of inequality of per capita sectoral emissions across sectors are then presented in the next section.

## 4.3 Results and discussion

With the help of Differential Evolution method, the inequality of per capita sectoral emissions in the form of Theil index among China, France, and the United States are optimized, to have the smallest gap of energy mix between 2050 and 2010 for each

country.

In this section, the optimization results of per capita sectoral CO<sub>2</sub> emissions are firstly compared under all CO<sub>2</sub> emission scenarios. Then the technology roadmaps in order to obtain the governmental target will be presented. At last, the sensitivity of parameters in the Sectoral Emission Model in the Policy scenario will be tested.

### 4.3.1 Sectoral per capita CO<sub>2</sub> emissions inequalities

In 2010, the Theil index of per capita CO<sub>2</sub> emissions from the power sector was 0.12, the Theil index of per capita CO<sub>2</sub> emissions from the transport sector was 0.7, and the Theil index of per capita CO<sub>2</sub> emissions from the other sector was 0.03. The sum of the Theil index of the three sectors was 0.85, which was half of the world's level, but two thirds more than the OECD level in 2010. The inequality of per capita emissions from power sector among the three countries is smaller than the OECD countries and the world's level. But the inequality of per capita emissions from transport sector among the three countries is larger than the OECD countries and the world's level.

The optimized inequality of per capita emissions from each sector among the three countries under the CO<sub>2</sub> emission scenarios in 2050 are shown in the figure 4.3:

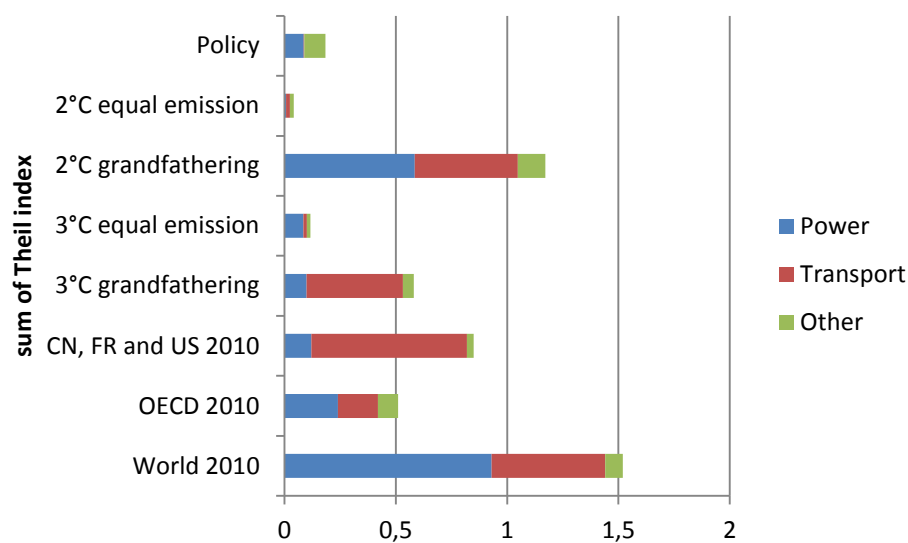


Fig.4.3. Inequality of per capita sectoral CO<sub>2</sub> emissions in 2050

From this figure above, we can see that in the five CO<sub>2</sub> emissions scenarios in 2050, only the sum of inequality in the 2°C grandfathering scenario is higher than the 2010 level in the three countries. That is because of the large differences of CO<sub>2</sub> emissions among these three countries in 1990. The smallest sum of inequalities is obtained in the 2°C equal emission scenario, which is only 5% of that in 2010. The second best inequality is in the 3°C equal emission scenario, where the sum of sectoral inequalities is 14% of that in 2010. In the Policy scenario, the sum of per capita sectoral emission inequality is 22% of that in 2010, which is higher than in the 2°C and 3°C equal emission scenarios, but lower than the 2°C and 3°C grandfathering scenario.

In 2010, the per capita emissions in the United States were the highest among the three countries, at 17.3t. The per capita emissions in China and in France are nearly the same level, at 5.4t and 5.5t respectively.

In 2050, in the **3°C grandfathering scenario**, the per capita emissions in the United States are still the highest, at 13.1t. However, the per capita emissions are 5.6t in China, higher than the level in France at 4.9t. In the power and transport sectors, the Theil indices are 0.098 and 0.432 respectively, which are 82% and 62% of the 2010 level, as shown in the table 4.1. But the Theil index of other sector in 2050 will be 0.0498 among the three countries, which is 66% higher than the level in 2010. Although the inequality of per capita emission from power sector increase, but the sum of the Theil index is one third smaller than that in 2010.

In the **3°C equal emission scenario**, the per capita emissions among the three countries are the same at 1.58t in 2050 with the world population estimation of 9.55 billion. The per capita emissions in the 3°C equal emission scenario is lower than all the per capita emissions of the three countries in the 3°C grandfathering scenario. Actually, it is 32% of that in the 3°C grandfathering scenario in France, 28% in China, and 12% in the United States. The inequality in the 3°C equal emission scenario is 0.0843 in the power sector, 0.0158 in the transport sector, and 0.0166 in the other sectors, which is 70%, 2% and 55% respectively of the 2010 level. The sum of the Theil index is 0.1166, 14% of that in 2010, and lower than the sum of Theil index in the 3°C grandfathering scenario of 0.3038.

In the **2°C grandfathering scenario**, the emissions in 2050 will be half of that in

1990 for each country. In 1990, the per capita emissions in the United States were the highest among the three countries, at 19.4t. The per capita emissions are 6.2t in France, and 2.0t in China. In 2050, in the 2°C grandfathering scenario, the per capita emissions will be 6t in the United States, 2.4t in France and 0.87t in China. The optimized sum of inequalities of sector per capita is 1.172 in the 2°C grandfathering scenario, 38% more than that in 2010, because the difference in per capita emissions among these countries is larger than that in 2010. The Theil index of the sectoral per capita emissions. The Theil index is 0.5851 in the power sector, 0.4627 in the transport sector, and 0.1241 in the other sectors. The inequalities of per capita emissions from sectors are much larger in the power sector and other sectors. Only in the transport sector, the inequality of per capita emission is less than that in 2010.

In the **2°C equal emission scenario**, the CO<sub>2</sub> emissions in 2050 are allocated according to the population size to countries, based on equal emission right accounting method. The global CO<sub>2</sub> emissions in 2050 are expected to be half of the level in 1990 in order to control the global temperature rise under 2°C. Thus, the per capita emission will be 1.1t for each country, as shown in the figure 4.9. It is 18% of that in the 2°C grandfathering scenario in the United States, 46% in France, and 126% in China in 2050. The inequality in the 2°C equal emission scenario is 0.0067 in the power sector, 0.0178 in the transport sector, and 0.0166 in the other sectors, which is 6%, 3% and 55% respectively of the 2010 level. The sum of the Theil index is 0.0412, 5% of that in 2010, which is the lowest inequality level in all the five scenarios.

In the **Policy scenario**, the inequality is 0.0853 in the power sector, 0.0027 in the transport sector, which is 71%, 0.4% respectively of the 2010 level. But the inequality in the other sectors is higher than in the 2010 level, with its Theil index at 0.0950, 217% more than that in 2010. The sum of the Theil index is 0.183, 22% of that in 2010, which is higher than the inequalities in the 2°C equal emission scenario and 3°C equal emission scenario, but lower than the 3°C grandfathering scenario, and 2°C grandfathering scenario.

The details of Theil index of the per capita emissions in 2050 from the power sector, transport sector, and other sectors are presented in the table 4.1, with the ratio to their 2010 level in the parenthesis.

**Tab.4.1. Theil index of per capita sector emissions under all scenarios**

<b>Theil index (% 2010)</b>	<b>Power</b>	<b>Transport</b>	<b>Others</b>
<b>3°C grandfathering scenario</b>	0.098 (82%)	0.432 (62%)	0.0498 (166%)
<b>3°C equal emission scenario</b>	0.0843 (70%)	0.0158 (2%)	0.0166 (55%)
<b>2°C grandfathering scenario</b>	0.5851 (488%)	0.4627 (66%)	0.1241 (414%)
<b>2°C equal emission scenario</b>	0.0067 (6%)	0.0178 (3%)	0.0166 (55%)
<b>Policy scenario</b>	0.0853 (71%)	0.0027 (0.4%)	0.0950 (317%)

In brief, the inequality levels of per capita CO<sub>2</sub> emissions from three main energy sectors are compared under different scenarios in this section. Even the governmental targets are not as ideal as the equal emission allocation objective in reducing the carbon inequality, but they will help to get better carbon equities than the grandfathering allocation approach.

In the next section, we will present the technology roadmaps in the Policy scenario, under the optimization framework by choosing carbon equity as the objective.

### **4.3.2 Roadmaps for Policy scenario**

In the Policy scenario, the CO<sub>2</sub> intensity will be reduced by 90% in 2050, and the CO<sub>2</sub> emissions are expected to be reduced by 75% in France and 83% in the United States. Under this target, the per capita emissions will be the highest in China at 4t. It is 2.4t in the United States and 1.2t in France in 2050, as shown in the figure 4.4:

- The equal emissions in France in 2050 according to the governmental target is nearly the same level of that in the 2°C equal emission scenario, which is 1.1t. It is 22% of the level in 2010, almost the lowest emission among all the scenarios.
- The equal emissions in the United States in 2050 according to the governmental target are the second lowest emissions among all the

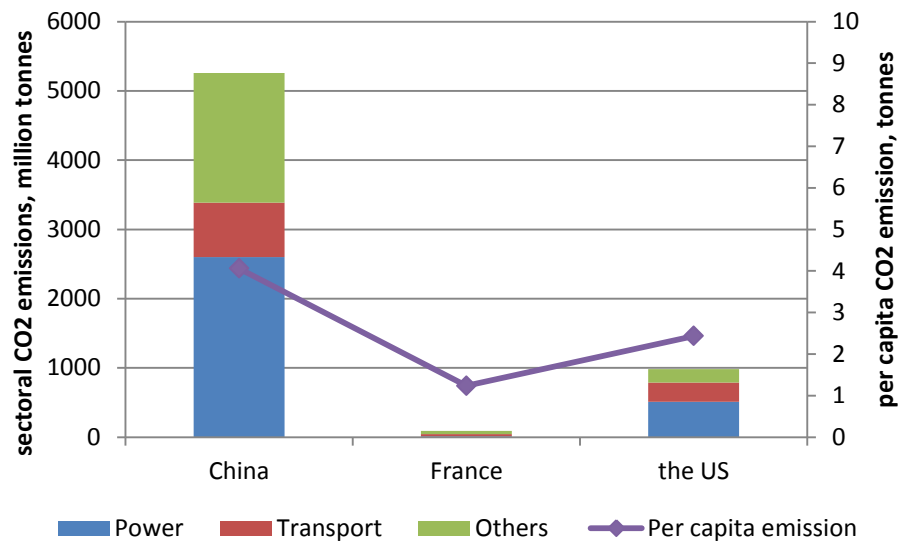


scenarios. It is twice of that in the 2°C equal emission scenario, and 14% of that in 2010.

- However in China, the per capita emissions in 2050 according to the governmental target are nearly four times of that in the 2°C equal emission scenario, which are the second highest emissions among all scenarios.

Under the optimization of per capita emissions from different sectors, the decomposition of CO<sub>2</sub> emissions from the power sector, transport sector and other sector in the Policy scenario are shown in the figure 4.4:

- In China, the CO<sub>2</sub> emissions in the power sector will be 49.5% of the total emissions in 2050. The transport sector will account for 14.9% emissions, and 35.6% of the total emissions will come from the other sectors. The shares of sectors are similar to that in 2010, showing that the reduction will be carried on through all sectors.
- In the United States, the share of emissions in the power sector will increase to 52.1% of the total emissions. The CO<sub>2</sub> emissions from the transport sector will stay unchanged at 28.4%, and 19.4% of the CO<sub>2</sub> emissions will come from the other sectors. This distribution of emissions across sectors shows that all sectors will have to make large reduction of emissions in order to achieve the Policy scenario.
- In France, the share of emissions in the power sector will be reduced to 10.8%. The CO<sub>2</sub> emissions from the transport sector will increase to 39.5% of the total emissions. And 49.7% of the CO<sub>2</sub> emissions will come from the other sectors. This distribution of CO<sub>2</sub> emissions requires efforts in the reduction of emissions in all sectors.



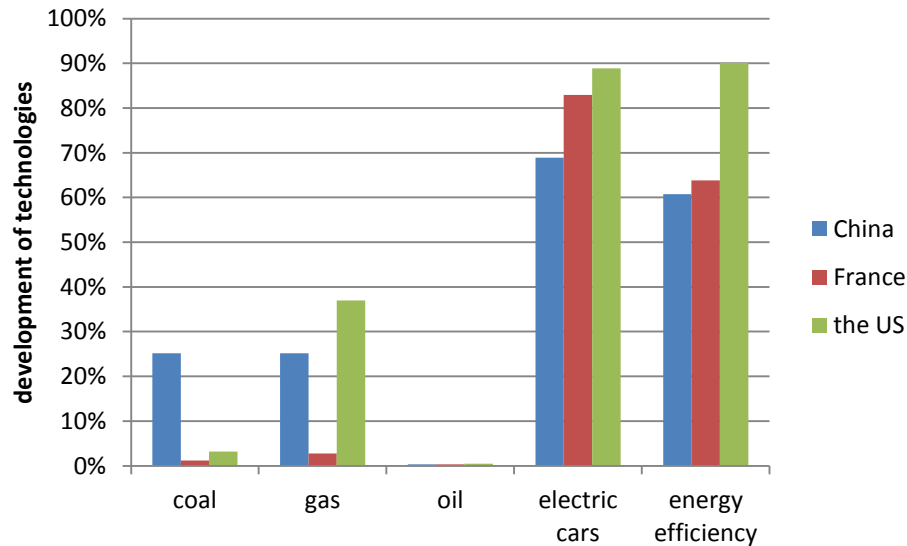
**Fig.4.4. Sector per capita emission inequality for Policy scenario**

The corresponding technology roadmaps in the optimization for the Policy scenario are then presented in the figure 4.5. In this scenario, the CO<sub>2</sub> emissions are lower than all the scenarios except the 2°C equal emission scenario in France and the United States. However, the Policy scenario allows the emissions to be higher than all the scenarios except the 3°C grandfathering scenario in China. This is because the government target is bounded with the economy development, which is expected to grow at a high rate in the future:

- In China, the share of coal and gas will be both reduced to 25% in the power sector in China in 2050. In the transport sector, 69% of vehicles will be changed to electric vehicles. And the energy efficiency in the residence and industry sector will be increased by 61% in 2050.
- In the United States, the share of coal will be reduced to 3% and the share of gas is to be increased to 37% in the power sector. 89% of vehicles should be changed to electric vehicles and the energy efficiency in the residence and industry sector should be improved by 90% in 2050.
- In France, the share of coal will decrease to 1% and the share of gas will decrease to 3% in the power sector in 2050. 83% of vehicles should be changed to electric vehicles and the energy efficiency in the residence and

industry sector should be improved by 64% in 2050.

Although the emissions are nearly the same in the Policy scenario and in the 2°C equal emission in France, the technology roadmaps are different. More electric vehicles should be employed in the Policy scenario, and more energy efficiency should be improved in the 2°C equal emission scenario.



**Fig.4.5 Technology roadmaps for Policy scenario in optimization**

This optimization of carbon equity is carried out with our Sectoral Emission Model, with the same assumptions of parameters in Chapter 3. In the next section, we will test the sensitivity of these parameters for this roadmap in the Policy scenario.

### **4.3.3 Test of sensitivity of parameters for Policy scenario**

In the previous Chapter 3, we have made assumptions for the parameters. The most important parameters are the five parameters as follows: the CO<sub>2</sub> emission intensities of production of fossil fuels, the electricity output, the number of vehicles, in the Sectoral Emission Model.

For the CO<sub>2</sub> emission intensities of production of the fossil fuels in China, France,

and the US in 2050, we assume that they will be the same level of those in Europe in 2010, as the CO<sub>2</sub> emission intensities of production in Europe are the world's lowest level in 2010. For the electricity output, we made the projection with SVR model based on the past twenty years' data. As to the number of vehicles, we assume that it will keep increasing at the growth rate in 2010 at about 1% in France and the United States, as their car numbers were growth at a stable rate. However, because the car numbers were increasing fast in the past few years in China, we assume that the car numbers will increase firstly at a rapid rate as in 2010 at 10%, and then this growth rate will progressively decrease to 1% in 2050.

The assumptions of parameters will certainly influence the modeling results. Thus, in order to make a robust calculation, we will test the sensitivities of the five parameters above in this section. This test is carried out based on the roadmap in the Policy scenario proposed by the optimization of per capita sectoral CO<sub>2</sub> emissions, as shown in the previous section.

The table 4.2 presents the influences by 1% of diminution of the parameters on the total CO<sub>2</sub> emissions. The influence of emission intensity of production of oil is not significant because the oil is barely used in the power sector:

- In China, the improvement of CO<sub>2</sub> emission intensity of production of coal is three time more important than the emission intensity of production of gas, with the same share of these two fuels in the power generation. The electricity output parameter is the most important parameters among the five parameters. One more percent of electricity production will add 0.481% to the total CO<sub>2</sub> emissions. As to the car numbers, one more percent cars will lead to an increase of emissions only by 0.0135%, thanks to 69% of electric cars utilization.
- In France, the sensitivities of emission intensities of production are not significant because the shares of these fossil fuels are negligible. Although the transport sector plays a more important role than the power sector in the CO<sub>2</sub> emissions, the electricity output is more important than the car numbers. One more percent electricity output will increase 0.1% of the CO<sub>2</sub> emissions. As to the transport sector, with 83% of electricity

cars used, the car number is the least important parameter.

- In the United States, the share of gas will be ten times more than the share of coal, so the sensitivity of emission intensity of production of gas is higher than that of coal, even though the emission intensity of production of coal is four times of that of gas. Same as in China and France, the sensitivity of electricity output is the highest among all the parameters. In the transport sector, with nearly 90% of electricity cars, the sensitivity of car numbers is smaller than the sensitivities of coal, gas, and electricity output, but higher than that in the other two countries.

**Tab.4.2. Sensitivity of parameters on the CO<sub>2</sub> emissions**

$\Delta(-1\%)$	$e_{\text{coal}}$	$e_{\text{oil}}$	$e_{\text{gas}}$	Car number	Electricity output
<b>China</b>	-0.3937%	-0.0025%	-0.0983%	-0.0135%	-0.4810%
<b>France</b>	-0.0635%	-0.0077%	-0.0367%	-0.0070%	-0.1009%
<b>The United States</b>	-0.1308%	-0.0094%	-0.3810%	-0.0263%	-0.4949%

In brief, under the roadmaps in 2050 in expecting to achieve the governmental reduction targets with the minimum per capita CO<sub>2</sub> emissions sectoral emissions, the parameters in the Sectoral Emission Model have different importance. The electricity output is the most important parameter which influences the CO<sub>2</sub> emissions in all the three countries. The emission intensity of production of coal in China and the emissions intensity of production of gas in the United States have nearly the same sensitivity, which means to reduce about 0.4% of total CO<sub>2</sub> emissions if its emission intensities of production are reduced by 1%. The sensitivity of coal in China and of gas in the United States is higher than that of other fossil fuels in their countries due to the large share of the corresponding fuel utilization. And because the shares of oil are all negligible in the energy mix, the emission intensity of production of oil in the three countries is the smallest. For the car numbers, due to the large employment of electricity vehicles, it has a relative small sensitivity on the CO<sub>2</sub> emissions.

## 4.4 Conclusion and discussion

In the internationalization proceeding, the development of technology will be shared by more and more countries. The convergence of technologies in the energy sectors will lead to more equal per capita emissions. In this Chapter 4, we determined the technology pathways in 2050 for China, France and the United States, by optimizing the inequality of per capita emissions in the energy sectors, under different CO<sub>2</sub> emission scenarios, especially for the Policy scenario. The Theil index was adopted in order to measure the per capita sectoral emissions inequality, and the Differential Evolution method was employed to carry out a multi-objective optimization, which allows minimizing the capita sectoral emission inequality.

As expected, in the 3°C and 2°C equal emission scenarios, the inequalities of per capita sectoral emissions are respectively smaller than those in the 3°C and 2°C grandfathering scenarios. The smallest inequalities of per capita sector emissions are obtained in the 2°C equal emission scenario, where all sectors in the three countries are expected to make large efforts in achieving the reduction of CO<sub>2</sub> emissions. The use of fossil fuels in the electricity production will be largely reduced, in which coal should be nearly abandoned in the energy mix in the three countries, with its share under 4%. However, gas could be used in power production, with 14% in China and 6% in the United States, as its emission intensity of production is much smaller than coal. In the road transport, the electric vehicles should be largely adopted in 2050 in all of the three countries, with 80% in China, 86% in France, and 90% in the United States. Meanwhile, the energy efficiency in the residence and industry sectors should be improved by 78% in France, by 91% in China, and by 95% in the United States.

In contrast, the biggest inequalities of per capita sector emissions are in the 2°C grandfathering scenario, bigger than the 2010 level, as the results of the large differences of CO<sub>2</sub> emissions among the three countries in 1990. In the 2°C grandfathering scenario, the technology pathway in China is similar to that in the 2°C equal emission scenario, with 2% of coal and 10% of gas, and 7% more electric vehicles are to be employed and energy efficiency to be improved by 2 more percent than in the

2°C equal emission scenario. In France and in the United States, less technology advancement is expected than in the 2°C grandfathering scenario. In France, 40% less electric vehicles are used, and 20% less energy efficiency are expected to be improved than in the 2°C equal emission scenario. In the United States, the power sector is far away from decarbonization, with 27% of coal and 22% of gas used in the power production. Besides, 20% less electric vehicles are employed and 10% less energy efficiency improved than in the 2°C equal emission scenario.

Similar to the 2°C scenario, the inequality of per capita sectoral emissions in the 3°C equal emissions are inferior to that in the 3°C grandfathering scenario. In the 3°C grandfathering scenarios, both coal and gas could be kept used in China and the United States (55% of coal and 11% of gas in China, 63% of coal and 28% of gas in the United States). However, gas is expected to replace coal in the power sector in the 3°C equal emission scenario, at 43% in China and 41% in the United States. Besides, compared to the 2°C equal emission scenario, 40% less electric vehicles will be used in the 3°C grandfathering scenario in France and in the United States, but 40% more electric vehicles should be employed in the transport sector in China. In the residence and industry sector, the energy efficiency should be more improved by 16% in China, 22% in France and 49% in the United States in the 3°C equal emission scenario than in the 3°C grandfathering scenario.

All these scenarios above are set under the ideal allocation approaches. Here in this last chapter, we focused on the technology pathways for obtaining the governmental targets, as described in the Policy scenario. In this scenario, the differences in the per capita CO<sub>2</sub> emissions across countries are smaller than in the 2°C and 3°C grandfathering scenarios, and thus the sectoral inequalities in the Policy scenario are smaller than those in the 2°C and 3°C grandfathering scenarios. Coal will be limited (25% in China and 3% in the United States) but gas will be encouraged (25% in China and 37% in the United States) in the electricity production. Electric vehicles will be largely used in France by 83% and in the United States by 89%, but less in China at 69%. The energy efficiency will be improved by about 60% in China and in France, but higher in the United States at about 90%. In the transport and other sectors, the technology advancement are similar to that in the 2°C equal emission scenario in

France, similar to that in the 3°C and 2°C equal emission scenario in the United States, and similar to that in the 3°C grandfathering scenario. The governmental targets cannot have the ideal carbon equity as in the per capita emission allocation, but they can make a smaller inequality of per capita sectoral emission than in the default allocation method, i.e. grandfathering. Besides, this optimization method can also help to propose their technology roadmaps in achieving the minimum carbon inequality.

The most important parameters in our Sectoral Emission Model: the emission intensities of production of fossil fuels, the electricity output and the car numbers are tested by their sensitivities on the emissions based on the roadmaps in the Policy scenario. The result shows that the parameters in the power sector play the most important role in influencing the CO<sub>2</sub> emissions, especially the electricity output in the Policy scenario. The sensitivities of emission intensity of production of different fossil fuels are determined by their mix and their intensity of production level. And because of the large adoptions of electric cars in the Policy scenario, the sensitivities of car numbers are not significant (-0.0135% in China, -0.007% in France and -0.0263% in the US).

The advantage of this optimization method is that it considers the different energy structures in different countries. The roadmaps are obtained not only by the minimum inequality of per capita sectoral emissions, but also by the minimum gaps of energy mix between 2010 and 2050, in different countries. The optimization of per capita emissions across sectors presents the possibilities of technology pathways in convergence to the benchmark country, which is France in this work.

This method would be a supplementary optimization method in cooperation with the generally-used cost-effective optimization in studying the energy transition, as in the following studies (Gambhir et al., 2013; IEA, 2014; Jiang et al., 2013; Kainuma et al., 2013; Krewitt et al., 2007; Sano et al., 2015; Zhou et al., 2012).



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# Chapter 5

## Conclusion and perspectives for technology roadmaps for CO<sub>2</sub> emissions

### 5.1 Introduction

The purpose of this thesis was to show both the extent of the possible alternatives in technology roadmaps and the technological constraints that must prevail in reaching the targets of reducing CO<sub>2</sub> emissions in 2050. Thus, we have proposed a Sectoral Emission Model through simulations which were conducted for China, France and the United States<sup>25</sup>.

In fact we have proposed an updating of an old modeling approach of polluting emissions that was firstly attributed to the Japanese economist Kaya and that was taken over later through the IPAT identity or STRIPAT approach. Our sectoral model for CO<sub>2</sub> emissions borrows from these approaches and attempted to improve them by the means

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<sup>25</sup> As we have presented in previous chapter: these three countries have been chosen as the objective countries, with one developing country China that is the world first emitter, and two developed countries with France and its low emission intensity of production and the United States with a high CO<sub>2</sub> intensity of production. In 2010, the GDP per capita was \$7.3 thousand in China, \$35 thousand in France, and \$47 thousand the United States. However, the per capita CO<sub>2</sub> emission was 5.5t in both China and France, and 17t in the United States.

of new quantitative methods and recent data. Our national bottom-up model was designed to propose technology roadmaps for the main energy sectors under different CO<sub>2</sub> scenarios.

This model covers the main energy sectors that contribute the most part of CO<sub>2</sub> emissions, i.e. more than 80% from the power, transport, residence, and industry sectors in 2010. In these sectors, we have focused on the main energy related technologies which are respectively the energy mix in the power sector, the Carbon Capture and Storage technology (CCS), the electric vehicles, the energy efficiency in the residence and the industry sectors.

Then we have examined two main issues in this thesis. First, the technology advancements in the main energy sectors within the different situations of the countries in achieving their particular objectives of CO<sub>2</sub> emissions (in Chapter 3). Second, the influence of the convergence of the technologies of energy sectors on the carbon equity (in Chapter 4).

The plan of this conclusion is as follows.

- First we will sum up the main results of the chapters in the thesis and we will point out the main characteristics of the technology roadmaps related to the governmental targets of CO<sub>2</sub> emissions reductions.
- Then the contributions on the energy system modelling of this thesis related to climate issues will be presented.
- In the end we will discuss the limits and perspectives of this work.

## **5.2 Summary of main results on the technology roadmaps**

### **5.2.1 The CO<sub>2</sub> emission scenarios**

In this work, our objective is to evaluate the governmental targets for reducing CO<sub>2</sub> emissions in 2050 for three types of countries. As the reference scenarios, the Business-as-Usual (BaU) scenarios of the countries and the climatic objectives of the scientific community, i.e. the 3°C and 2°C scenarios are also studied. Each scenario of climatic objective is subdivided by two different approaches: equal emission convergence approach and grandfathering approach, according to different carbon equity principles.

Among the scientific community objectives, the CO<sub>2</sub> emission level is the lowest for France and the United States in the 2°C equal emission scenario. However in China, the lowest emission level is in the 2°C grandfathering scenario, as the result of its low emissions in the bench year of 1990.

The governmental target is between the 2°C grandfathering scenario and the 2°C equal emission scenario in France and the United States. In China, the governmental target is more tolerant, which is between the 3°C grandfathering scenario and the 3°C equal emission scenario, due to its objective of reducing CO<sub>2</sub> intensity (CO<sub>2</sub> emissions per GDP) instead of reducing CO<sub>2</sub> emissions.

### **5.2.2 The simulation methods**

In order to make a robust simulation of the parameters in the modeling, various methods are employed according to the different requirements of parameters. First of all, the CO<sub>2</sub> emissions in the BaU scenario are projected with STIRPAT – for Stochastic Impacts by Regression on Population, Affluence and Technology – model, which projects the future CO<sub>2</sub> emissions based on the historic trends, and future population

and economy evolutions. For the power sector, its CO<sub>2</sub> emissions are decomposed through IPAT identity (which assumes the environment Impact is the results of Population, Affluence and Technology), into the production of electricity and technology. Then, the Support Vector Regression (SVR) is used for the forecasts the production of electricity, as it is an appropriate simulation method for a small database.

### 5.2.3 Technology pathways

Based on our Sectoral Emission Model, we have first proposed two types of technology pathways for reaching CO<sub>2</sub> emission reduction target of nations: by balanced technology development criteria and least change of energy mix criteria.

**In China**, if the energy mix is expected to be changed at minimum in 2050 in terms of that in 2010, all the automobiles would be changed into electric vehicle, with the energy efficiency in the residence and industry sectors improved by 90%. Then the share of coal should be decreased by 20% if CCS is not employed. If CCS is used, the energy mix can be kept unchanged in 2050, with 40% of electric vehicles employed and energy efficiency improved by 40%. If technologies are advanced homogenously in all sectors, then 60% of coal should be reduced if CCS is not used (20% if CCS is used), with 60% of electric vehicle and 60% of improvement of energy efficiency.

**In France**, the power sector contributes little to the CO<sub>2</sub> emissions thanks to the use of nuclear, thus the CCS is not considered in the power sector. Meanwhile, the energy roadmaps for balanced technology development and least changed energy mix are nearly the same: 80% of the automobiles are expected to be changed into electric vehicles, and the energy efficiency in the residence and industry should be improved by 80%.

**In the United States**, if the energy mix is expected to be changed the minimum in 2050 as in 2010, all the automobiles should be replaced by electric vehicle, with the energy efficiency in the residence and industry sectors improved by 90%, same as in China. Then the share of coal should be decreased by 30% if CCS is not employed. If CCS is used, the energy mix can be kept unchanged in 2050, with 80% of electric

vehicles employed and energy efficiency improved by 80%. If technologies are advanced homogeneously in all sectors, then 40% of coal should be reduced if CCS is not used (20% if CCS is used), with 80% of electric vehicle and 80% of improvement of energy efficiency.

#### **5.2.4 Carbon equity with Theil index**

Besides the technology roadmaps above, we have proposed the technology roadmaps by applying the optimization of carbon equity by sectors, under the assumption of the convergence of technologies across countries in the future. The Theil index is employed as the measurement for inequality of per capita CO<sub>2</sub> emissions. We have adopted the Differential Evolution as the optimization methodology. This multi-objective optimization allows to minimize the carbon inequality in the three main sectors, and also to minimize the change of energy mix in each country between 2050 and 2010.

We have conducted the optimization for all scenarios. As expected, in the 3°C and 2°C equal emission scenarios, the inequalities of per capita sectoral emissions are respectively smaller than those in the 3°C and 2°C grandfathering scenarios. The lowest inequalities of per capita sector emissions are obtained in the 2°C equal emission scenario. In contrast, the highest inequalities of per capita sector emissions are in the 2°C grandfathering scenario, even higher than the 2010 level, as the results of the large differences of CO<sub>2</sub> emissions among the three countries in the bench year of 1990. The inequality of per capita sectoral emissions of the governmental target is higher than in the 3°C and 2°C equal emission scenarios, but lower than in the 3°C and 2°C grandfathering scenarios. In the energy roadmaps for governmental target, the combustion of coal should be reduced to 25% in China and 3% in the United States. However, the use of gas will be increased to 25% in China and 37% in the United States in the electricity production, due to the low emission intensity of production of gas. In the transport sector, 83% of electric vehicles will be used in France, 89% in the United States by 89%, and 69% in China. In the residence and industry, energy efficiency will



be improved by about 60% in China and in France, higher in the United States by about 90%.

### 5.2.5 Sensitivity analysis

In addition, we have tested the sensitivities of these parameters on the emissions, at each step of the work, for all the technology roadmaps. The results show that electricity production and emission intensity are two parameters with the most important influence on CO<sub>2</sub> emissions. Thus improving the efficiency of coal combustion and the energy efficiency of electricity will play an important role in the CO<sub>2</sub> emission reductions.

## 5.3 My Contributions to the energy system and climate change models

There are three main contributions in this work. **The first is the proposition of the sectoral emission model:** which is based on existing models of the literatures; but we have applied them to climate change and improved them with scenarios, quantitative approaches and the latest available data. The classic bottom-up energy models generally employ the framework of cost-effective optimization, which intend to propose the technology pathways in minimizing the total cost of energy systems. Compared to the classic cost-optimizing energy models, our model can be used as a complementary approach for assessing technology roadmaps under flexible criteria.

This model proves to be simple and flexible. It is simple in terms of the modeling framework, which focuses on the principle energy sectors and principle energy technologies. It is flexible because it is possible to add new technology adoptions, and the sectors can be desegregated. Besides it is possible to customize the model framework to numerous demands according to the energy structure of the country.

Another advantage of keeping the flexibility of the sectoral emission model is that

different criteria can be applied in the modeling, for example the balanced development of technologies across sectors, the least change of energy mix, and the minimal carbon equity of sectors (as presented in this work).

**The second contribution is the assessment of the policy targets for CO<sub>2</sub> emission reductions, for three canonical countries, with their possible technology roadmaps.** We have studied the policy targets of countries in comparing with the global reduction target like IPCC scenarios, by subdividing them with different allocation methods in terms of different equity principles. We have proposed different technology roadmaps corresponding to the particular situation in each country (as presented in Chapter 3). We have shown that sometimes high level of substitutions were possible in the mix of energy. We have found some results were ambitious (see the share of electric vehicles for instance).

**The third contribution is the evaluation of carbon equity in assessing technology roadmaps.** In most of the literature on energy transition (as presented in Chapter 2), the technology roadmaps are evaluated by the cost-optimizing approach. In this work, we have proposed the technology roadmaps through the optimization of sectoral carbon equity (in Chapter 4). This approach is proposed under the consideration of the technology convergences in each sector of energy, which is appropriate and relevant for the assessment of technology roadmaps for long-term. The key idea here is that ‘technologic champions’ could appear in the future and then they could be shared or supplied in all countries.

## **5.4 Limits and research perspectives on the modeling of Sectoral emissions of CO<sub>2</sub>**

Our thesis has limits, and some improvements could be expected in future works. Firstly, we have mainly studied the power sector and the transport sector, which are the

two largest emitters of CO<sub>2</sub> emissions from fuel combustions. In the residence and industry sectors, we used the general notion of energy efficiency as the technology in reducing CO<sub>2</sub> emissions. In the future work, **the residence and industry sectors** could be subdivided if we are interested in the detailed technologies in these two sectors. For example, the applications by different level of energy efficiency, the isolation of buildings in the residence sector, the recycle of products in the production, the energy efficiency in the production in the industry sector, etc. could be added in the modelling.

Secondly, we have made some **strong assumptions of parameters** in the modeling, as there are no robust predictions to be adopted for these parameters. For instance, we use the CO<sub>2</sub> emission intensity of fossil fuels in 2010 in Europe, which represents the lowest level as the level for each country in 2050. For the car number, we assumed that it will keep grow with the current rate till 2050 in the developed countries. In the developing countries, it has a high growth rate nowadays but gradually the growing rate will decrease to the same level as in the developed countries, due to the saturation of the market in long term. In future works, these parameters could be adapted to countries with different assumptions in consideration of different situations.

Meanwhile, some other factors can be added in the modeling: for example the tolerance on nuclear plants of the public, the infrastructures for the electric vehicles (charging points, capacity of battery), etc.

Thirdly, we have studied the sectoral carbon equity over the energy transition period, but we did not consider **the constraint of cost in the adoption of technologies**, which is also a crucial factor in the policy making. Our approach can be served as a supplementary method for the classic cost-optimizing approach in the energy transition. In future works, cost-effective optimizing could complete the multi-objective optimization in our model. Or the technology roadmaps by different criteria are to be completed with the intervals of cost, according to the studies on economic projections.

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**Titre :** Transition Énergétique et Inégalité de Carbone : Une Analyse Prospective des Feuilles de Route Technologiques pour la Chine, la France et les États-Unis d'Amérique.

**Mots clés :** scénarios prospectifs d'émissions de CO<sub>2</sub>, inégalités carbone, transition énergétique, modélisation des émissions sectorielles, roadmaps technologiques, optimisation multi-objectifs

**Résumé :** Dans le contexte du réchauffement climatique global, les institutions académiques et internationales comme GIEC et de nombreux pays ont proposé des objectifs de réduction des émissions de CO<sub>2</sub>. L'objectif de cette thèse est d'évaluer ces objectifs gouvernementaux en les comparant avec les objectifs globaux à l'aide de différentes méthodes d'allocations lesquelles correspondent à différents principes d'équité en matière d'émissions carbone.

Afin d'évaluer les feuilles de route technologique permettant d'obtenir les réductions d'émission de CO<sub>2</sub> nécessaires, un modèle qualifié de flexible est proposé à destination des décideurs. Notre modèle permet d'éviter les opérations informatiques complexes et peut être personnalisé en fonction de différents besoins. Les simulations sont réalisées jusqu'à l'horizon 2050 lequel est souvent considéré comme un pivot dans les habitudes de consommation d'énergies notamment.

Dans cette thèse, des feuilles de route technologique pour les différents objectifs gouvernementaux en matière d'émissions de CO<sub>2</sub> sont étudiées pour trois pays : la Chine, la France et les États-Unis. Le modèle couvre les principaux secteurs responsables des émissions de CO<sub>2</sub> et étudie l'influence de différentes technologies sur le mix énergétique.

Diverses méthodes et approches sont utilisées dans notre modélisation. L'identité IPAT est utilisée pour la décomposition des émissions dans les secteurs de l'énergie. Le modèle STIRPAT permet quant à lui d'évaluer l'évolution des émissions de CO<sub>2</sub> dans les scénarios Business-as-Usual. Le modèle SVR est utilisé dans le cadre des projections de production d'électricité. Enfin, l'indice de Theil est employé pour mesurer les inégalités d'émissions de CO<sub>2</sub> par tête.

A la différence des modèles plus classiques en économie de l'énergie, notre modèle propose des feuilles de route technologiques selon différents critères, comme par exemple avec le développement « équilibré » de la technologie entre

les secteurs, ou le critère de disponibilité des ressources énergétiques. Par ailleurs, l'équité carbone, avec la convergence des technologies dans les secteurs à long terme, peut être mise en œuvre dans notre modèle et joue, dans ce cas, comme une contrainte supplémentaire dans l'optimisation multi-objectifs.

Nos résultats montrent que les objectifs gouvernementaux en France et aux États-Unis sont « très stricts » car, pour les atteindre, tous les secteurs doivent réaliser des efforts importants de réduction de CO<sub>2</sub>. En revanche, l'objectif gouvernemental de la Chine s'avère « plus facile » à réaliser car les progrès dans les technologies qui sont nécessaires sont moins exigeants.

Plus précisément, si on prévoit que le mix énergétique reste inchangé en Chine et aux États-Unis, le CSC deviendra indispensable dans le secteur de l'énergie. Pour la France, 80% des voitures devront être remplacées par des véhicules électriques afin d'atteindre son objectif en matière de CO<sub>2</sub>.

Toutefois, en considérant l'équité carbone entre secteurs, la combustion du charbon est censée être réduite de deux tiers en Chine et devra être pratiquement éliminée aux États-Unis. Par contre, le gaz peut être encouragé dans son utilisation dans le secteur de l'énergie en particulier aux États-Unis. Concernant le secteur du transport, plus de 60 % des véhicules doivent être remplacés par des véhicules électriques en Chine. Cette part serait d'environ 90 % en France et aux États-Unis.

Enfin, la sensibilité des paramètres du modèle a été testée pour simulations, à chaque étape du travail, et pour toutes les roadmaps technologiques. Les résultats des tests de sensibilité montrent que la production d'électricité et l'intensité d'émissions sont les deux paramètres dont l'influence est la plus importante sur les émissions futures de CO<sub>2</sub>. Ainsi l'amélioration de l'efficacité de la combustion du charbon et de l'efficacité énergétique de l'électricité joueront un rôle central dans la réduction des émissions de CO<sub>2</sub>.

**Title :** Energy Transition and Carbon Inequality: Prospective analysis of Technology Roadmaps for China, France and the United States of America

**Keywords :** CO<sub>2</sub> emission prospective scenarios, carbon inequality, energy transition, sectoral emission modeling, technology roadmaps, multi-objective optimization.

**Abstract :** In the context of global warming, academic institutes, international institutions such as the IPCC, and governments of numerous countries have proposed global objectives of reducing CO<sub>2</sub> emissions and announced national targets. The purpose of this thesis is to assess the governmental targets in comparing with the global objectives of various allocation methods, which correspond to different carbon equity principles.

In order to evaluate the technology roadmaps which are necessary to achieve these reductions of CO<sub>2</sub> emissions, a flexible modeling framework is proposed for policy makers. Our sectoral model avoids the complex computing operations. It can be customized according to different requirements and situations. We simulate the model up to the horizon 2050, which is often seen as a turning point in energy use patterns worldwide – forced by the probable decline in hydrocarbons extraction.

In the thesis, the technology roadmaps for the governmental targets on CO<sub>2</sub> emissions are studied for three typical countries: China, France, and the United States. The model covers the sectors responsible for the greatest part of CO<sub>2</sub> emissions: power, transport, residence and industry sector, in studying the impacts of the principle energy technologies, such as energy mix, Carbon Capture and Storage (CCS), electric vehicles and energy efficiency.

Various methods and approaches are used in our modeling. IPAT identity - which assumes the environment Impact is the results of Population, Affluence and Technology - is employed in the power sector emission decomposition. Besides STIRPAT - for Stochastic Impacts by Regression on Population, Affluence and Technology - model is used for the projection of CO<sub>2</sub> emissions in the Business-as-Usual scenario. Then SVR - for Support Vector Regression - is used to forecast electricity production. Finally, the Theil index is employed as the measurement of per capita CO<sub>2</sub> emission inequality.

Different from classic cost-effective energy system models, our model provides the technology pathways for different criteria, such as balanced development of energy technology across sectors, availability of energy resources, etc. Besides, the carbon equity is employed as one of the constraints in the multi-objective optimization, under the consideration of the convergence of technologies in sectors in the long-term.

Our results show that the governmental targets in France and the United States prove very strict, as they require all sectors to make large efforts in reducing CO<sub>2</sub> emissions. In contrast, the governmental target in China seems more easily achievable, as the necessary advances of technologies are less demanding.

More precisely: if the energy mix is expected to be kept unchanged in China and in the United States of America, the CCS prove indispensable in the power sector. In France, 80% of automobiles are required to be changed into electric vehicles, in order to get the target of CO<sub>2</sub> emissions.

However, under the sectoral carbon equity consideration, coal combustion is projected to be reduced by two thirds in China, and it will have to be almost eliminated in the United States to achieve their CO<sub>2</sub> reduction target. But gas is encouraged to be used in the power sector, especially in the United States. Regarding the transport sector, more than 60% of vehicles should be replaced to electric vehicles in China, and this share will be about up to 90% in France and the United States.

Finally the sensitivity of parameters in the model is tested for a robust simulation, at each step of the work, and for all technology roadmaps. The results of the sensitivity tests show that electricity production and the emission intensity of production are the two parameters with the most important influence on CO<sub>2</sub> emissions. Thus improving the efficiency of coal combustion and the energy efficiency of electricity will play an important role in the CO<sub>2</sub> emission reductions.