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# Inequalities of Sectors CO<sub>2</sub> emissions in China, USA and France, 2010-2050

Wenhui TIAN<sup>1</sup>, Pascal DA COSTA<sup>1</sup>, Jean-Claude BOCQUET<sup>1</sup>

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**Abstract:** In the context of global warming, academic institutes, international institutions such as the Intergovernmental Panel on Climate Change and governments of numerous countries have proposed global objectives of reducing CO<sub>2</sub> emissions and announced national targets. The purposes of this article are: *i*) to assess the governmental targets in comparing with the global objectives of various allocation methods, which correspond to different carbon equity principles; *ii*) to propose technology roadmaps in terms of carbon equity in the energy sectors, under the consideration of the international convergence of technologies in the energy transition period up to 2050. In order to evaluate the technology roadmaps, a Sectoral Emission Model is proposed that 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 (energy mix, electric vehicles and energy efficiency). In the article, 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. Our results show that 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.

**JEL Codes:** Q47; Q54. **Keywords:** CO<sub>2</sub> Emission Prospective Scenarios; Carbon Inequality; Energy Transition; Sectoral Emission Modeling; Technology Roadmaps; Multi-Objective Optimization.

## 1. Introduction

As mandated by the United Nations Framework Convention on Climate Change, the stabilization of Greenhouse Gas (GHG) emission concentration 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> emissions are sub-products of economic activities (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 relevant 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 years or periods, 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 work, we propose 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 many studies (Cornell et al., 2012; Da Costa and Shoai Tehrani, 2013; Finon and Perez, 2008; Mosseri and Jeandel, 2013; Zaccai et al., 2012).

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This scenario will be studied in details in this article. 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 (US). In this work, 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.

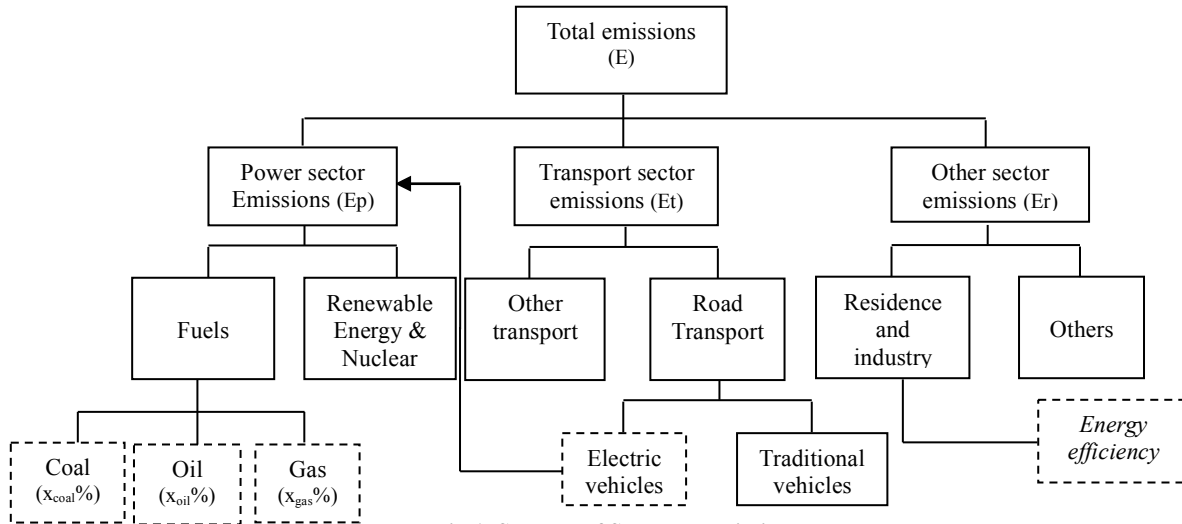
The optimization of sector per capita emissions equity is based on the Sectoral Emission Model (Da Costa and Tian, 2015), a flexible model which can be applied with various criteria. We aim to find the technology pathways in the context of realizing the best equity of per capita emissions across sectors under certain emissions scenarios, by introducing a benchmark nation: here is France. Why we 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 US, 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 calculations.

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 US. However, gas is encouraged to be used in the power sector, especially in the US. As to the transport sector, electric vehicles in China should replace more than 60% of vehicles. This share will be about 90% in France and the US. In the residence and industry sector, the energy efficiency should be improved by about 50% in China and France, 70% in the US. 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 US 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 reminder of this work is organized as follows. The section 2 will introduce the Sectoral Emission Model. The section 3 will present the data and CO<sub>2</sub> emission scenarios, and the section 4 presents the optimization method and inequality index. In section 5, the results of the multi-objective optimization will be discussed. And section 6 concludes the work.

## **2. Sectoral Emission Model**

The structure of the model is presented in the figure 1 (Tian and Da Costa, 2013, 2014b). The 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.



**Fig.1. 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. This model is applied in this study as it can be used with different criteria for the technology roadmaps. The variables are shown in the dotted line in the figure.

### 3. Data and scenarios

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 and 2°C scenario by equal emission; 3) The Policy scenario: here we will focus on the Policy scenarios, and the other scenarios are set to be different reference scenarios.

**1) Business-as-Usual (BaU) scenario:** 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 (as shown in Annex A).

**2) World reference scenarios:** 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°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 US 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 US 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 US 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 US in 2050.

**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>2</sup> (ERI, 2009) compared to 2005, and this objective is extensible 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 US 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>3</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>4</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 2. 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 40 years. In the Untied 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 US. 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 US. 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 US.

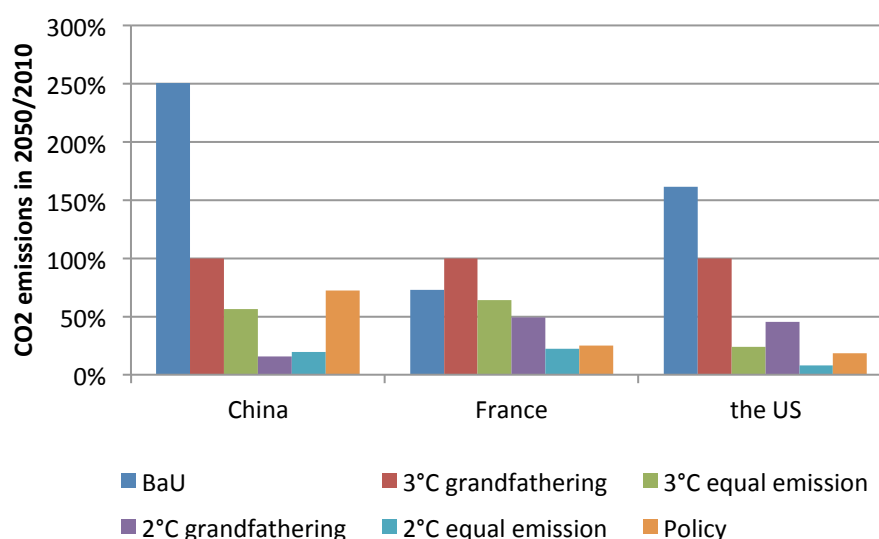


Fig.2. National emissions by scenarios in 2050 compared to the 2010 level

#### 4. Optimization methodology

This section presents the inequality index to measure the per capita emissions inequalities, and the optimization method that minimizes the inequality per capita emissions across sectors. The per capita

<sup>2</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>3</sup> In 2013, the GHG emissions were 9% below 2005 level, according to the “U.S. Greenhouse Gas Inventory Report: 1990-2013”.

<sup>4</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)”.

sectoral emission inequality of all CO<sub>2</sub> emission scenarios will be optimized via the Differential Evolution method. Then we will discuss the technology roadmaps in the Policy scenario, in comparison with other scenarios.

#### 4.1. 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.

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.<sup>5</sup> 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. In this work, we adopt the Theil index, even though there are not standard criterions 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:

$$T(c, p) = \sum_i p_i * \ln\left(\frac{\bar{c}}{c_i}\right) \quad (1)$$

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 2 to 4:

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

$$\sum p_i * \ln(\bar{c}_{\text{power}}/c_{i,\text{power}}) \quad (2)$$

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

$$\sum p_i * \ln(\bar{c}_{\text{transport}}/c_{i,\text{transport}}) \quad (3)$$

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

$$\sum p_i * \ln(\bar{c}_{\text{other}}/c_{i,\text{other}}) \quad (4)$$

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

##### 4.1.1. Constraint equations:

We employ the Sectoral Emission Model (Da Costa and Tian, 2015). 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:

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<sup>5</sup> 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.

$$\begin{aligned}
& \text{Total emissions}_{\text{scenario},i} \\
& = (\text{electricity output}_{2050,i} + 0.73 * y_i * N_{2050,i}) * (x_{\text{coal}} * e_{\text{coal}} + x_{\text{oil}} * e_{\text{oil}} + x_{\text{gas}} * e_{\text{gas}}) \\
& \quad + \text{Transport emissions}_{2050,i} * (1 - y_i) + \text{Other emissions}_{2050,i} * (1 - e_i)
\end{aligned} \tag{5}$$

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:

$$\begin{aligned}
0 & \leq y_i \leq 1 \\
0 & \leq e_i \leq 1 \\
(x_{\text{coal}} + x_{\text{oil}} + x_{\text{gas}})_i & \leq 1
\end{aligned} \tag{6}$$

In the optimization, the energy mix among France, China and the US 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:

$$(x_{\text{coal}}, x_{\text{oil}}, x_{\text{gas}})_{2050,FR} \leq (x_{\text{coal}}, x_{\text{oil}}, x_{\text{gas}})_{2010,FR} \tag{7}$$

#### 4.1.2. 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:

$$\min \left\{ [\sum p_i * \ln \left( \frac{\bar{c}_{\text{power}}}{c_{i,\text{power}}} \right)]^2 + [\sum p_i * \ln \left( \frac{\bar{c}_{\text{transport}}}{c_{i,\text{transport}}} \right)]^2 + [\sum p_i * \ln \left( \frac{\bar{c}_{\text{rest}}}{c_{i,\text{rest}}} \right)]^2 \right\} \tag{8}$$

In China, France and the US, 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:

$$\min [\sum (x_i - x_{2010})^2] \tag{9}$$

#### 4.2. 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 US.

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

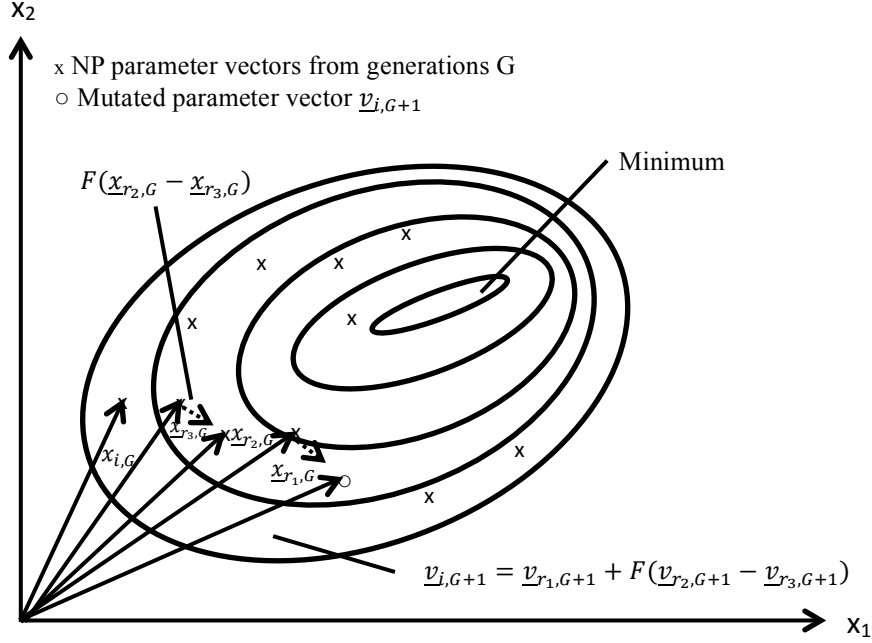
$$x_{i,G}, i = 1, 2, \dots, NP \tag{10}$$

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 :

$$v_{i,G+1} = x_{r_1,G} + F * (x_{r_2,G} - x_{r_3,G}) \quad (11)$$

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 3 shows a two-dimensional example that illustrates the different vectors which play a part in the generation of  $v_{i,G+1}$ .



**Fig. 3. 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:

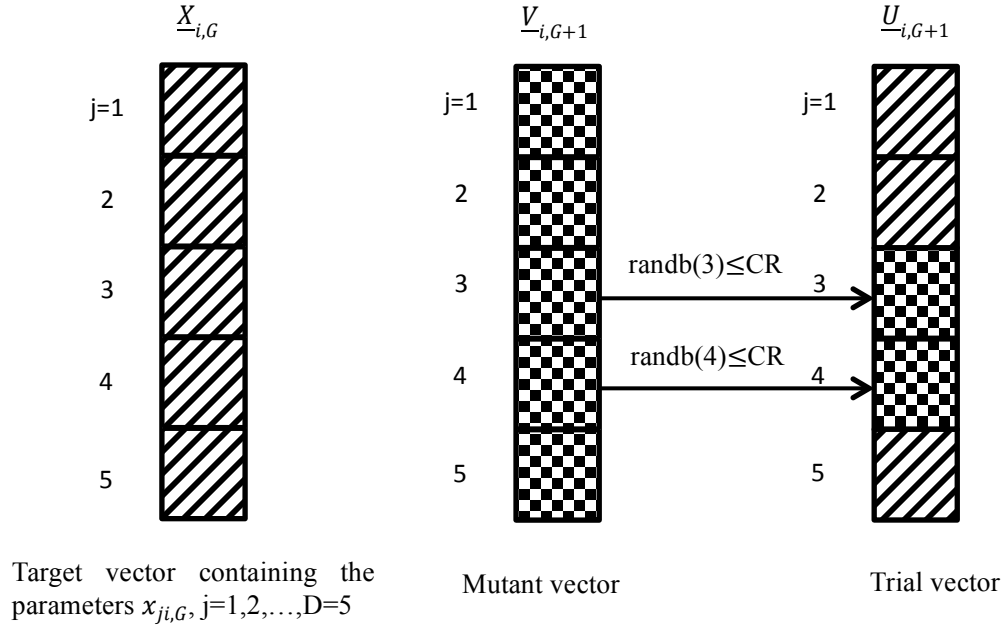
$$u_{i,G+1} = (u_{1i,G+1}, u_{2i,G+1}, \dots, u_{Di,G+1}) \quad (12)$$

with:

$$u_{ji,G+1} = \begin{cases} u_{ji,G+1} & \text{if } (randb(j) \leq CR) \text{ or } j = rnbr(i) \\ u_{ji,G} & \text{if } (randb(j) > CR) \text{ and } j \neq rnbr(i) \end{cases} \quad (13)$$

$j = 1, 2, \dots, D.$

where the  $randb(j)$  is the  $j^{th}$  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 gives an example of the crossover mechanism for 5-dimensional vectors.



**Fig.4. 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.

## 5. Results and discussion

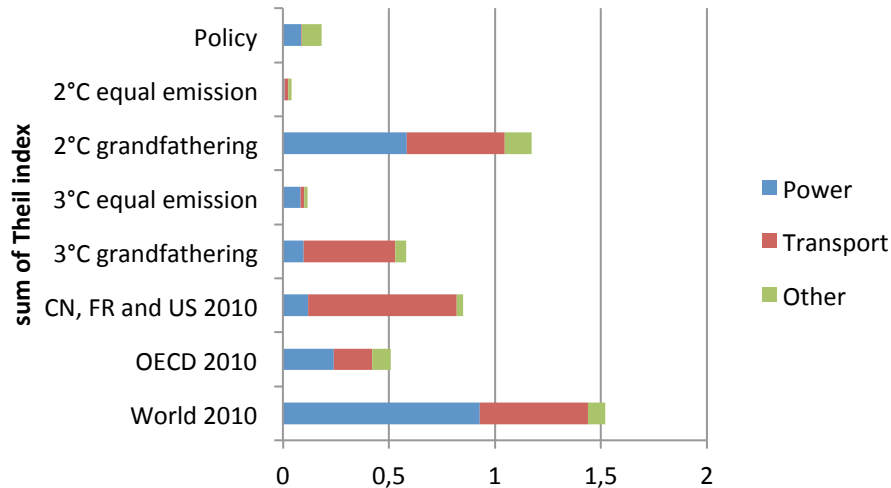
With the help of Differential Evolution method, the inequality of per capita sectoral emissions in the form of Theil index among China, France, and the US are optimized, to have the smallest gap of energy mix between 2050 and 2010 for each country.

In this section, the optimization results of per capita sectoral  $\text{CO}_2$  emissions are firstly compared under all  $\text{CO}_2$  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.

### 5.1. Sectoral per capita $\text{CO}_2$ emissions inequalities

In 2010, the Theil index of per capita  $\text{CO}_2$  emissions from the power sector was 0.12, the Theil index of per capita  $\text{CO}_2$  emissions from the transport sector was 0.7, and the Theil index of per capita  $\text{CO}_2$  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  $\text{CO}_2$  emission scenarios in 2050 are shown in the figure 5:



**Fig.5. 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 US 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 US 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 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 US. 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 US 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 US, 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 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 6. It is 18% of that in the 2°C grandfathering scenario in the US, 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 1, with the ratio to their 2010 level in the parenthesis.

**Tab.1. Theil index of per capita sector emissions under all scenarios**

Theil index (% 2010)	Power	Transport	Others
<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.

## 5.2. Roadmaps for Policy scenario

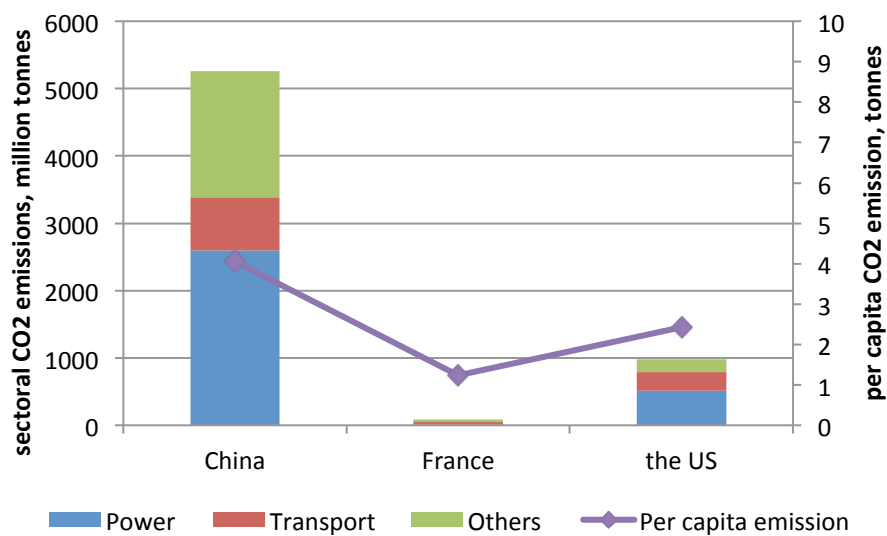
In the Policy scenario, the CO<sub>2</sub> intensity will be reduced by 90% in 2050, and the CO<sub>2</sub> emissions are expected to be reduced by 75% in France and 83% in the US. Under this target, the per capita emissions will be the highest in China at 4t. It is 2.4t in the US and 1.2t in France in 2050, as shown in the figure 5:

- 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 US 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 6:

- 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 US, 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.



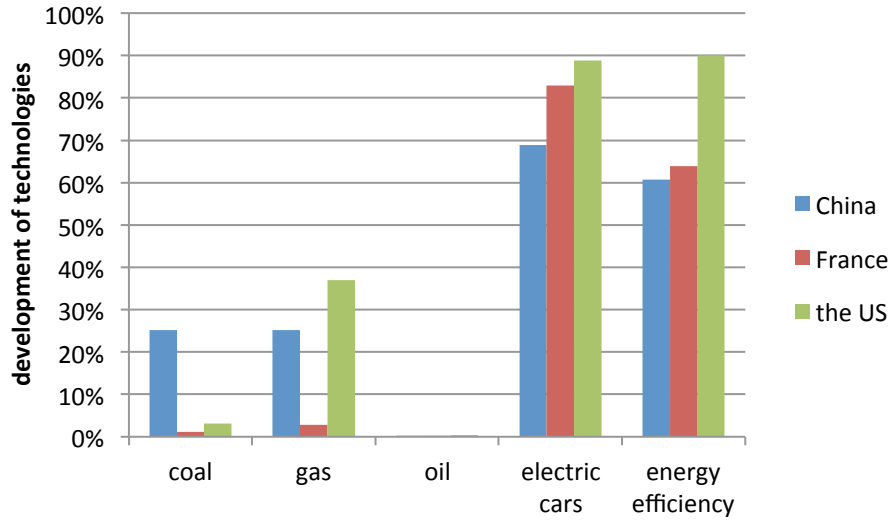
**Fig.6. Sector per capita emission inequality for Policy scenario**

The corresponding technology roadmaps in the optimization for the Policy scenario are then presented in the figure 7. 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 US. 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 US, 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.7. 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 the work of Da Costa and Tian (2015). In the next section, we will test the sensitivity of these parameters for this roadmap in the Policy scenario.

### 5.3. Test of sensitivity of parameters for Policy scenario

In order to make a robust calculation, we will test the sensitivities of parameters in the modeling. In the Sectoral Emission Model, 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 US, 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 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 US, 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.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 US 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 US 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.

## 6. Conclusion and discussion

In the internationalization proceeding, more and more countries will share the development of technology. The convergence of technologies in the energy sectors will lead to more equal per capita emissions. In this work, we have proposed the technology pathways in 2050 for China, France and the US, 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 US, 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 US. 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 US.

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 US, 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 US, 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 US (55% of coal and 11% of gas in China, 63% of coal and 28% of gas in the US). 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 US. Besides, compared to the 2°C equal emission scenario, 40% less electric vehicles will be used in the 3°C grand fathering scenario in France and in the US, 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 US 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. Under the governmental targets, 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 US) but gas will be encouraged (25% in China and 37% in the US) in the electricity production. Electric vehicles will be largely used in France by 83% and in the US 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 US 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 US, 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).

## **Annex A: Projection of population and GDP in 2050**

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 the article, 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 A1. 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. In France, the population will increase by 15%, from 62 million to 72 million. In the US, 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 Unites States by 7%, and in China by 30%.

**Tab.A1. Population scenarios by medium variant in 2050**

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

Besides 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 US 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 A2 presents the economy in the Baseline scenario in the three countries, according to the report “The world in 2050” (HSBC, 2011).

**Tab.A2. GDP (PPP) Baseline scenarios in 2050**

GDP ppp (billion dollars)	China	France	The United States
2050	57 784.54	5 339.13	38 060.89
2010	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 US.

### Annex B: Projection of CO<sub>2</sub> emissions in the BaU scenario in 2050

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:

$$I_i = a * P_i^b * A_i^c * T_i^d * e_i \quad (14)$$

where  $I$ ,  $P$ ,  $A$ ,  $T$  have the same signification as in the IPAT identity (1);  $i$  indicates the time series;  $a$  defines the scale of the model;  $b$ ,  $c$ , and  $d$  are the elasticities of  $P$ ,  $A$  and  $T$  respectively; and  $e$  is the error term<sup>6</sup>. In general the variables are introduced in a logarithmic form in the simulations:

$$\log I = \log a + b * (\log P) + c * (\log A) + \log e \quad (15)$$

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 B:

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

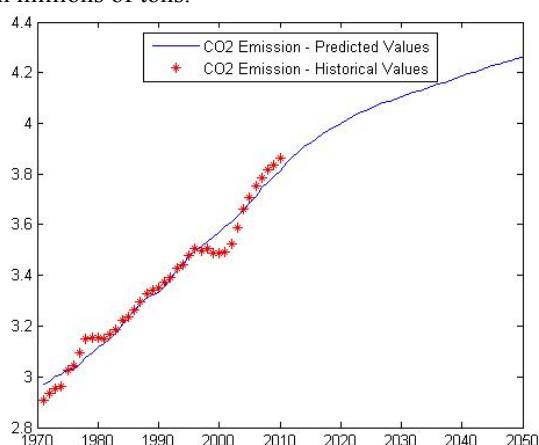
	Constant (loga+loge)	b	c	R <sup>2</sup>
China	-0.679 (-0.284)	0.6546 (1.648)	0.5688 (8.468***)	0.9755
France	3.3813 (0.650)	-0.0672 (-0.056)	-0.3416 (-0.929)	0.4338
United States	8.1599 (4.590***) <sup>7</sup>	-1.0816 (-2.825**)	0.9319 (4.702***)	0.8647

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.

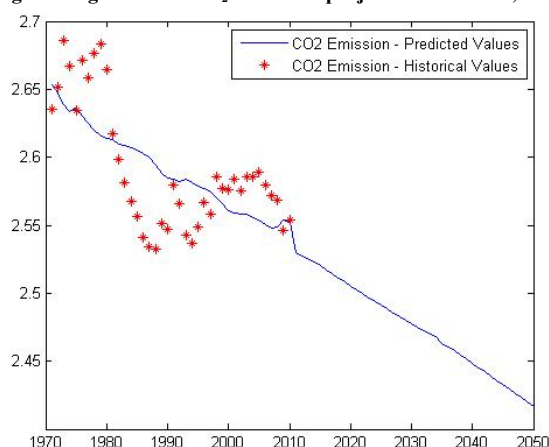
<sup>6</sup> If  $a = b = c = d = e = 1$ , the STIRPAT reduces to the IPAT identity and  $T$  is included in the error term (unlike in the IPAT identity, where  $T$  serves to balance the equation).

<sup>7</sup> The t-statistics are in parentheses. \*\* is the 0.001 significance level and \*\*\* the 0 significance level.

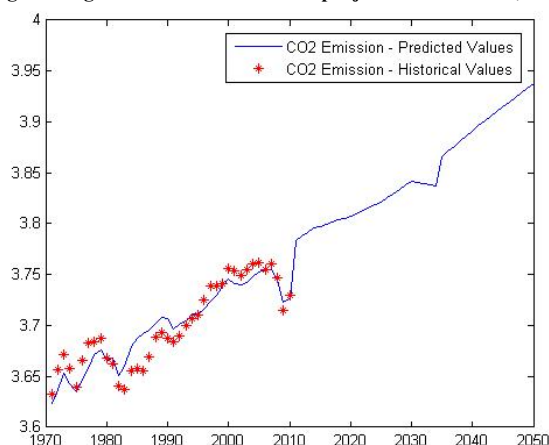
Figures B1 to B3 show the logarithm of CO<sub>2</sub> emissions in the three countries between 1971 and 2050. The X-axis is in years and the Y-axis in millions of tons.



**Fig.B1. Logarithm of CO<sub>2</sub> emissions projections in China, 1971-2050**



**Fig.B2. Logarithm of CO<sub>2</sub> emissions projections in France, 1971-2050**



**Fig.B3. Logarithm of CO<sub>2</sub> emissions projections in the US, 1971-2050**

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