A Sectoral Prospective Analysis of CO2 Emissions in China, USA and France, 2010-2050

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Abstract: In the context of global warming, many countries have announced their national targets in reducing their CO_2 emissions. In order to evaluate the technology roadmaps that are necessary to achieve these targets of CO_2 emissions, a flexible modeling framework is proposed in this article. This sectoral model avoids the complex computing operations and 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). The technology roadmaps for governmental targets on CO_2 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_2 emissions: power, transport, residence and industry sector, in studying the impacts of the principle energy technologies, such as energy mix, Carbon Capture and Storage, electric vehicles and energy efficiency. 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 sensitivity of parameters in the model is tested for robust simulations at each step of the work and for all technology roadmaps scenarios.

JEL Codes: Q47; Q54.

Keywords: STIRPAT Model; Support Vector Regression; Energy Transition; Sectoral Emission Modeling; Technology Roadmaps.

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 by Intergovernmental Panel on Climate Change (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 (IPCC, 2014). In this context, several countries have proposed their targets in reducing the CO_2 emissions, which is the most important gas among the Greenhouse Gases (GHG). In this article, our objective is to assess these policy targets by evaluating the technology roadmaps, in the period of energy transition, from 2010 to 2050.

Several families of applied models 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). However, 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). The complex models (MARKAL, AIM, NEMS, etc.) make a full coverage of the energy sectors and energy flues, but they also require 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 be representative of numerous other similar countries in the world: China (CN), a fast-emerging economy that requires increasing energy consumption, and the largest emitter of CO_2; France (FR), a well-developed economy with relatively low CO_2 emissions; and the United States (US), the largest economy and a major source of CO_2 emissions. All possible solutions for the technology pathways can be generated with our Sectoral Emission Model, offering the policy makers choices of technology transition solutions

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according to their different criteria. Besides the solution pool of the technology roadmaps, here we provide two more: under the assumption of "balanced technology development" across sectors what refers to the same improvement of each technology in reducing CO2 emissions ; and under that of "least changed energy mix" that refers to the minimization of the difference between the energy mix in 2050 and in 2010 for each country. In addition, the sensitivity of the model with parameters under these two roadmaps is tested.

The results of the model show that governmental targets in France and in the US require all sectors make large efforts in reducing CO_2 emissions. In France, two thirds of emission reductions are expected to be conbtributed by the transport sector. 80% of vehicles should be changed to electric vehicles for reaching its governmental target. Meanwhile, the energy efficiency should also be improved by 80%. As the power sector contributes little to the CO_2 emission, CCS is not a necessary option for France. In the United States, all sectors should make important contribution for reaching the governmental target. At least 80% of cars should be changed into electric cars, and the energy efficiency should be improved by at least 60%. In the power sector, the use of coal in 2050 can be kept at most half of that in 2010. However, for the governmental target in China, the advancement of technologies is less demanded than in France or in the US. In China, half of the emission reductions are expected to be contributed by the power sector, as the power sector accouts for half the the emissions in 2010. In order to achieve its governmetal target, 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 quite unchanged in China and in the US, 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_2 emissions (IPCC, 2005). However, this technology is not yet largely applied in the power sector and industry considering of security and high costs. Meantime, 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_2 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 paper is organized as follows: Section 2 introduces the structure of the Sectoral Emission Model. Section 3 presents the data for CO_2 emission objectives. Section 4 then explains the results obtained from the model according to different countries. Conclusions are drawn in the section 5.

2. The Sectoral Emission Modeling

The Sectoral Emission Model is proposed to evaluate the scientific relevance and feasibility of the CO_2 reduction target with respect to the population, economy and CO_2 emissions between 2010 and 2050, under the consideration of energy technology transition. Three sectors are considered: (i) electricity-generation, (ii) transport, and (iii) other, which include principally the residence and industry sector.

2.1. The Context

The figure 1 presents the CO_2 emissions and per capita CO_2 emissions of the representative three countries from 1971 to 2010. From 1971 to 2005, the US was the biggest sources of CO_2 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 US 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.

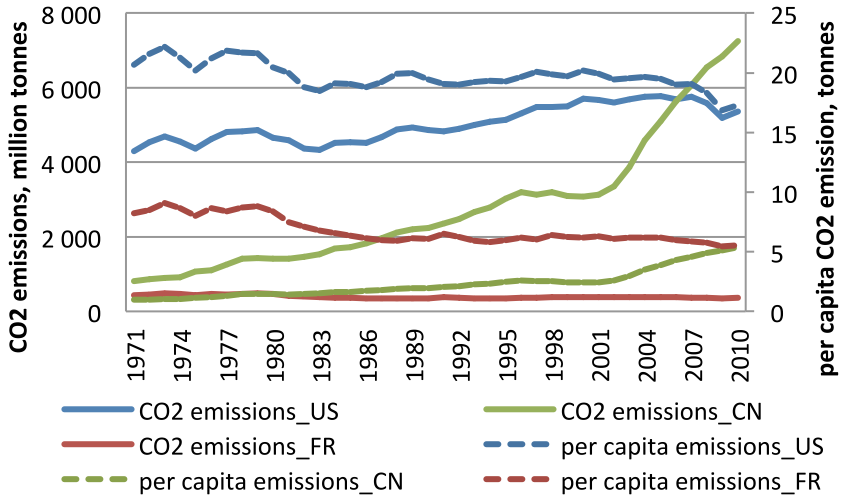

Fig.1. National CO_2 emissions and their per capita CO_2 emissions between 1971 and 2010

The table 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 US, 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 US. Even though the transport sector accounts for only 7% of CO_2 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 US. From table 1, we can observe that the emissions are distributed almost homogenously across sectors in France. 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.1. Sectoral emissions shares in 2010

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

The energy related technologies considered in this article are taking the power and transport sectors as the principal sources of CO_2 emissions. Energy mix, CCS, electric vehicles and energy efficiency are the key parameters in reducing CO_2 emissions.

2.2. The 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_2 emissions are mainly fossil fuels, namely coal, oil and gas. The sources which 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 2 (Tian and Da Costa, 2013, 2014):

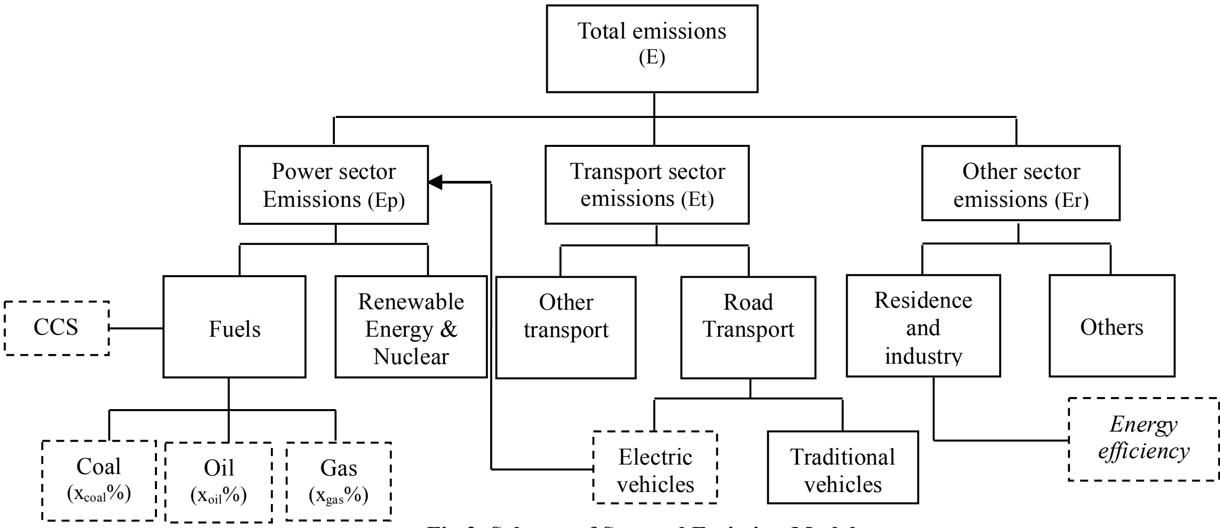

Fig.2. Schema of Sectoral Emission Model

As shown in the schema above, the total CO_2 emissions are the sum of the emissions from power sector, transport sector, and the other sectors:

$$E_{(t)} = E_{P(t)} + E_{T(t)} + E_{R(t)} \tag{1}$$

where $E_{(t)}$ is the total CO_2 emissions from fuel combustions in year *t*, and $E_{P(t)}$, $E_{T(t)}$ and $E_{R(t)}$ are CO_2 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 2. We principally analyze the power and transport sectors here, in which fuel mix, CCS and electric vehicles are three key factors behind CO_2 emissions. Improved energy efficiency in the domestic and industrial sector also contributes to CO_2 emission mitigation. The parameters and variables in the modeling will be explained according to sectors, in the flowing sub-section.

2.2.1. The power-generation sector

In the power sector, we employ the IPAT identity methodology to study the driving forces of the CO_2 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):

$$CO_2\ emissions = Population * \frac{GDP}{Population} * \frac{CO_2\ emissions}{GDP} \tag{2}$$

The IPAT identity had been developed later into Kaya identity (Kaya, 1989) which is widely used for CO_2 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_2 emissions can be decomposed into the product of three basic factors, carbon intensity of energy, energy intensity and affluence:

$$CO_2\ emissions = Population * \frac{GDP}{Population} * \frac{Energy\ consumption}{GDP} * \frac{CO_2\ emissions}{Energy\ consumption} \tag{3}$$

Inspired from the IPAT identity and Kaya identity, we decompose the CO_2 emissions in the power sector into the product of the output of electricity and the technology (i.e. the CO_2 emission intensity of production). And the fossil fuels, such as coal, oil and gas, are the three main sources contribute to CO_2 emissions in the power sector. Analytically, its emissions in year *t* are divided into these three categories as follows:

$$E_{P(t)} = \left(Q_t * \sum x_{i,t} * e_{i,t}\right) * \epsilon(\text{ccs}) \tag{4}$$

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_2 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. Support Vector Regressions (SVR) will be then used in order to simulate the projection of electricity output.

The variables and parameters in the power sector will be presented in the following three parts: first, the actual energy mix in the three countries; second, the projection of electricity output; third, the CCS technology.

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, 2011). France is one of the least CO_2 intensive industrialized economies, thanks to the substantial role of nuclear power and the existence of higher gasoline taxes with incentive impacts. CO_2 emissions have been declining since 2005 from an already relatively low base. In 2009, nuclear power accounted for 76.24% of France's electricity generation. The US depends on fossil fuels for almost all its energy supply. Natural gas use is rapidly growing in the US, 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 US, accounting for 45% of the country's electricity generation.

As a result of the different energy mix in the power sector, CO_2 emissions per KWh (the CO_2 emission intensity of production) from electricity generation vary greatly across countries. The figure 3 shows that CO_2 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 US, while nuclear power plants currently account for 80% of French electricity output.

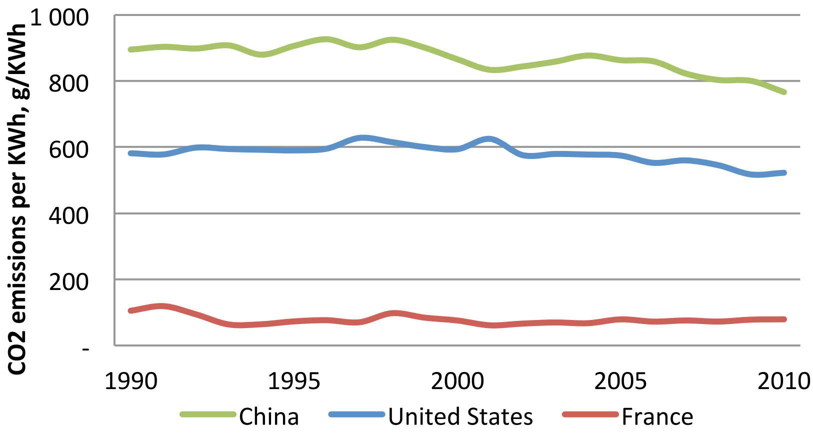

Fig.3. CO_2 emissions per KWh from electricity generation

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 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.2. CO_2 emission intensities of production of fossil fuels (IEA, 2012)

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

2) Electricity output

As to the electricity production, we will make the projection with the historical data between 1971 and

2010. We choose the SVR to carry out the simulation, because it 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.[2] 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 ε-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 $(\gamma * \vec{u} \cdot \vec{v} + \mathrm{coef})^{\mathrm{degree}}$ 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:

Tab.3. Values of the hyperparameters in electricity output

	C	Degree	ξ	ϒ	R^2
China	1	4	$1.0E^{-3}$	10	0.6478
France	1	4	$1.0E^{-3}$	10	0.7161
United States	1	4	$1.0E^{-3}$	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 US. Figures 4 to 6 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.

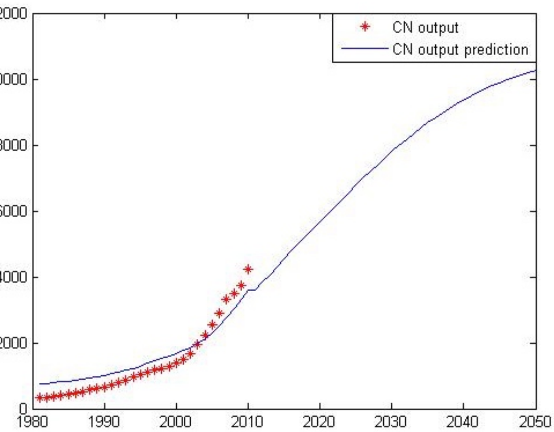

Fig.4. Electricity production in China 1981-2050

[2] 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.

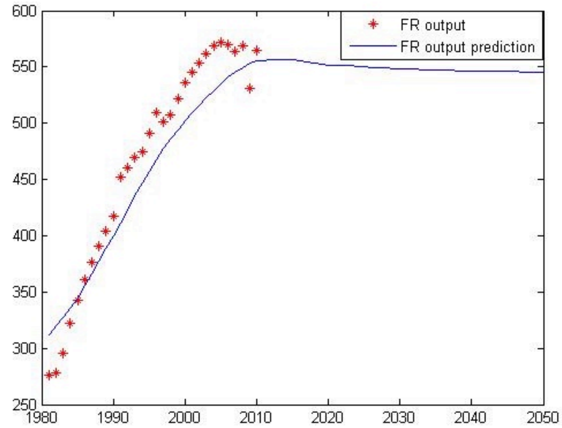

Fig.5. Electricity production in France 1981-2050

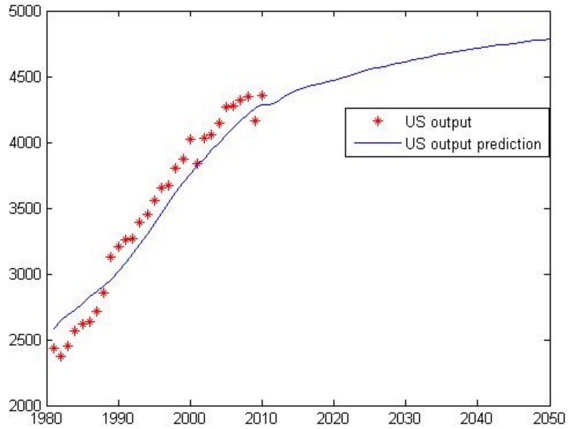

Fig.6. Electricity production in the US 1981-2050

3) 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_2 emissions from human activities. As CO_2 is emitted principally from the combustion 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_2, like the power plants. CCS involves the use of technology, first to collect and concentrate the CO_2 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_2 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_2 transport, and the type and characteristics of the CO_2 storage. In most CCS systems, the cost of capture is the largest cost component, in the range of 15-75 US$/t$CO_2$ net captured from a coal- or gas-fired power plant. The cost of transportation is between 1 US$/t$CO_2$ and 8 US$/t$CO_2$. The cost of storage is 0.5-8 US$/t$CO_2$ for geological storage and 5-30 US$/t$CO_2$ 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_2 emissions will be captured and stocked. Thus, we have the dummy variable $\epsilon(\text{ccs})$ to the equation 4, where:

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

2.2.2. The transport sector

The power generation sector makes the most important contribution to the global CO_2 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_2 emissions in 2010, of which 72% CO_2 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.

Now let's introduce the low-carbon emission vehicle.

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_2eq 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.

Now we present the situation of transport emissions in the three countries and the modeling method.

2) Road transport emission across the three countries

The transport sector is responsible for the largest share of CO_2 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 US had the most vehicles of any countries in the world (254 million), with transport accounting for 30% of CO_2 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_2 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 6), which makes a notable contribution to total electricity output.

The CO_2 emissions of the transport sector in year t are then calculated as:

$$E_{T(t)} = \frac{E_{road(t)}}{\alpha_{road}} = \frac{E_{road(2010)} * (1+\gamma)^t * (1-y_t)}{\alpha_{road}} \tag{5}$$

where $E_{T(t)}$ are CO_2 emissions in the transport sector in year t, $E_{road(t)}$ are CO_2 emissions from road transport in year t, γ is the vehicle growth rate, y_t is the proportion of hybrid vehicles in the vehicle stock in year t, and α_{road} is the share of road transport in the CO_2 emissions of the transport sector. The baseline CO_2 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_2 emissions in France will increase from 118mt to 198mt, and from 1400mt to 2170mt in the US.

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

$$E_P^{tr} = 0.73 * y_t * N_{(t)} \tag{6}$$

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 US, as their car number growth was at a stable rate[3]. However, because the car numbers were increasing fast in the past few years in China, we assume that the cars numbers will increase first at a rapid rate as in 2010 at 10%, and then this growth rate will progressively decrease to 1% in 2050[4].

The numbers of vehicles in 2050 in these countries are shown in the table 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 US, which means nearly one vehicle for one person.

Tab.4. Assumptions for number of vehicles in 2050

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

2.2.3. 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 Sectorial Emission Modeling, but the notion energy efficiency, which is employed to be the representative technology.

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.

[3] The projections of car numbers in France and the United States are more optimists 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.

[4] 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.

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_2 emissions accounted for 22.4% of those in the other sectors in the US; 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_2 emissions in the rest sectors other from power sector and transport sector are presented as follows:

$$E_{R(t)} = \frac{E_{RI(\mathrm{t})}}{\beta} = \frac{(1-e)*E_{RI(baseline)}}{\beta} \tag{7}$$

where $E_{R(t)}$ is CO_2 emissions from the other sectors in year t, $E_{RI(\mathrm{t})}$ is domestic CO_2 emission, e represents the improvement of domestic energy efficiency, $E_{RI(baseline)}$ is domestic CO_2 emission without taking energy efficiency into account, and β is the domestic share in other sector CO_2 emissions. The baseline domestic CO_2 emissions in China will increase from 303mt in 2010 to 458mt in 2050, and they will increase from 322mt to 430mt in the United Stated. However, the baseline emissions in the domestic will be reduced from 57mt to 39mt in France, because of the decreasing trend of CO_2 emissions in the past few years.

3. The Data

In this section, we present the governmental target for CO_2 emission reductions. The French government announced a reduction of CO_2 emissions by 75%[5] ("facteur 4") in 2050 compared to level in 1990 according to the "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_2 emission are expected to be 89mt in 2050.

The US House of Representatives passed the American Clean Energy and Security Act, which aimed to reduce 17% of their CO_2 emissions below the 2005 level in 2020[6], and 83% in 2050 (Waxman and Markey, 2009), which means that their CO_2 emissions are expected to be reduced to 981mt in 2050.

In 2009, China promised to reduce its CO_2 intensity (CO_2 emission per unit of GDP) by 40%-45% in 2020[7] (ERI, 2009) compared to 2005, and this objective is extenable to 85%-90% in 2050. In this work, we adopt the reduction of CO_2 intensity by 90% in 2050, which means the expected CO_2 emissions are 5 259mt in 2050, with the baseline scenario of GDP assumption[8].

[5] In 2012, the CO_2 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)".

[6] In 2013, the GHG emissions were 9% below 2005 level, according to the "U.S. Greenhouse Gas Inventory Report: 1990-2013".

[7] Actually, in 2013, the CO_2 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 governement, the objective of reducing CO_2 intensity in 2020 was not changed.

[8] This CO_2 emission is calculated with the baseline scenario of GDP according to the report "The world in 2050" (HSBC, 2011. The world in 2050: Quantifying the shift in the global economy. HSBC Global Research.). The GDP using Purchasing Power Parities (PPP) in China will be 57784 $billion in 2050, about six times of the 2010 level.

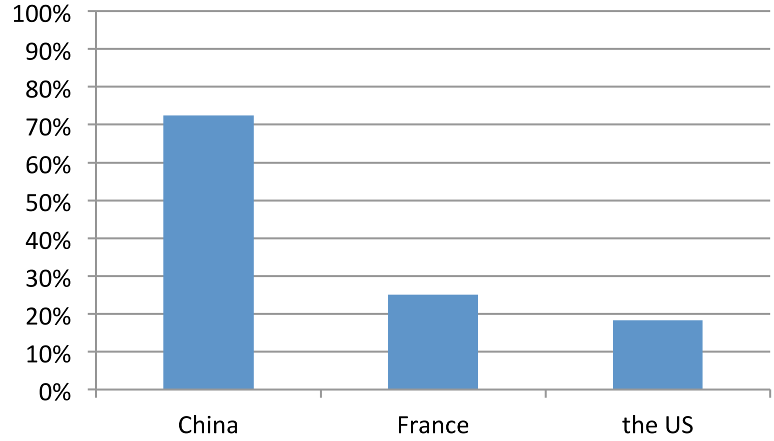

Fig.7. CO_2 emissions by governmental targets in 2050 compared to the 2010 level

The propotions of CO_2 emissions by governmental targets in 2050 relative to 2010 are shown in the figure 7. The emissions in 2050 will be 72% of that in 2010 in China, 25% in France and 18% in the US.

4. Results for technology roadmaps

The reduction of CO_2 emissions in the model are decomposed into the reductions of sectoral emissions, which means that the reductions of sectors are good substitutes. Thus, there is infinite technology pathways in meeting the scenario objective. Therefore we plan to present a solution pool of technology roadmaps only based on technology development. The energy related technolgies are: the share of coal and gas in the power sector[9], 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%][10]. In order to avoid the numberless solutions, we make these assumptions: *i*) the shares of electric vehichles are set from 0% to 100% with the interval of 20%; *ii*) the improvements of energy efficiency in the residence and industry sector are set from 0% to 80% with the interval of 20%.

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

4.1. Technology roadmaps in China

We first present the solution pool of the technology roadmaps for China. Then we present their 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 for China.

1) Technology solution pool in China

In China, half the CO_2 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_2 emissions in 2050, but its reduction of emissions can not be ignored due to the rapid growth of car numbers.

[9] 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%.
[10] The improvement of energy efficiency by 100% is not realistic as the emissions in the residence and industry cannot be eliminated perfectly.

According to the governmental target, the CO_2 intensity is projected to be reduced by 90% in 2050 with respect to 2005, which means that the CO_2 emissions will be reduced by 28% compared to the level in 2010. Different technology pathways are shown in the figure 8 without CCS and in the figure 9 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 incresed 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 equiped 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%.

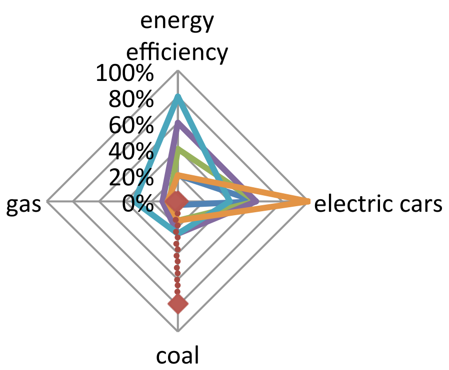

Fig.8. Technology roadmaps without CCS in China

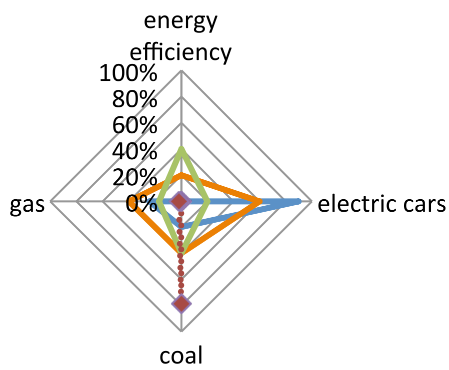

Fig.9. Technology roadmaps with CCS in China

As the energy technologies in the three sectors are substitutional, there will be infinite possiblities for the technology roadmaps. Among the different technology roadmaps in China in order to reach the governemental targets, we propose two roadmaps based on two criteria: one with balanced CO_2 emissions reduction across sectors, the other with least changed energy mix in the power sector. In each roadmap, the sensitivities of parameters: the CO_2 emission intensities of production of fossil fuels, the electricity output, and the number of vehicles, in the Sectoral Emission Model will be tested.

2) Balanced technology development roadmaps for China

Under the balanced technology development criteria, the technologies across sectors are supposed to be developped homogenously. The figure 10 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_2 intensity in 2050 with balanced technology development across sectors, electric vehciles 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_2 emissions reductions in the transport and other sectors. 35% of vehicles will be replaced by electric vehicles, and the energy efficieny 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_2 emissions.

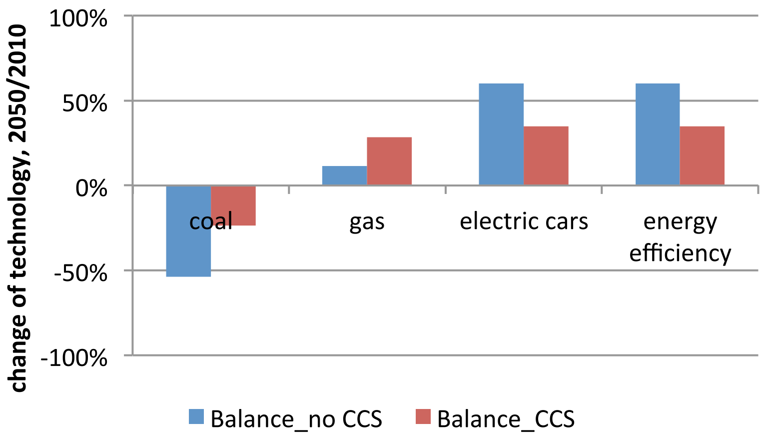

Fig.10. Technology roadmaps by balanced technology development in China in 2050 compared to 2010

There are three most important parameters in the modeling: 1) the CO_2 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 5 presents the influences by 1% diminution of the parameters on the total CO_2 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_2 emissions from fuel combustions. The second most important parameter is the CO_2 intensity of production of coal, because coal is the more used and more polluant 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.5. Sensitivity of parameters by balanced technology development on the CO_2 emissions in China

Δ (-1%)	e_{coal}	e_{oil}	e_{gas}	Car number	Electricity output
Balance_no CCS	-0.3896%	-0.0025%	-0.0507%	-0.0106%	-0.4322%
Balance_CCS	-0.0849%	-0.0002%	-0.0116%	-0.0014%	-0.0953%

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 11. 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_2 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 industy should be improved by 37%.

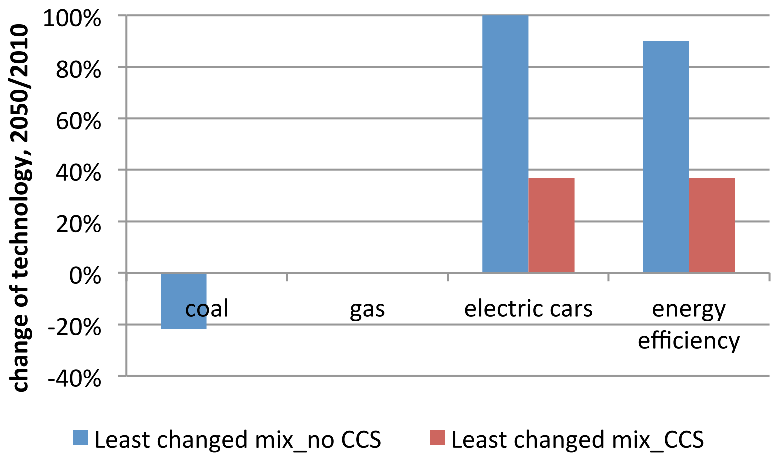

Fig.11. Technology roadmaps by least changed energy mix in China in 2050 compared to 2010

As to the sensitivities of parameters, the electricity output and the emission intenstity of coal have nearly the same sensitivities with or without CCS. Meanwhile, they have the most important sensitivities on the CO_2 emissions, as shown in the table 6. 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 electriciy output.

Tab.6. Sensitivity of parameters by least changed energy mix on the CO_2 emissions in China

Δ(-1%)	e_{coal}	e_{oil}	e_{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_2 emissions in 2050 are relatively tolerant. There are all kinds of technology roadmaps for reaching the governmental target. If the energy mix is planed 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_2 emissions. The emission intensity of production of coal and the electricity are the two parameters with most important sensitivity on the CO_2 emissions, for both the balanced technology development roadmap and the least changed energy mix roadmap.

4.2. Technology roadmaps in France

In France, nearly 80% of the electricity is now produced by nuclear power. The CO_2 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 techonology 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 countries).

According to French "facteur 4", the CO_2 emissions in 2050 are planned to be reduced to 25% of the level in 1990. The transport sector is still the most imporant sector in the contributions to the emission reductions. The technology pathways are prensented in the figure 12. 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%.

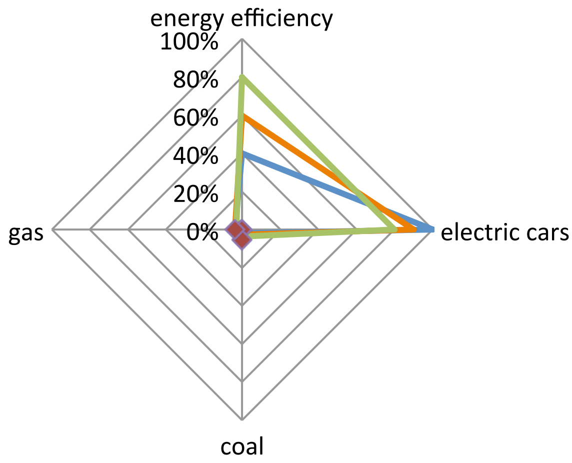

Fig.12. Technology roadmaps without CCS in France

As in France, the share of coal and gas are very small, the power sector will not contribute much to the CO_2 emission reductions. Actually, the roadmaps with the balanced technology development and the least energy mix are basiclly the same. Thus here we only discuss the balanced technology development roadmaps. Then we will present the sensitivities of parameters: the CO_2 emission intensities of production of fossil fuels, the electricity output, the number of vehicles in the Sectoral Emission Model.

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_2 emissions will be reduced in the power sector and other sectors. In the figure 13, 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%.

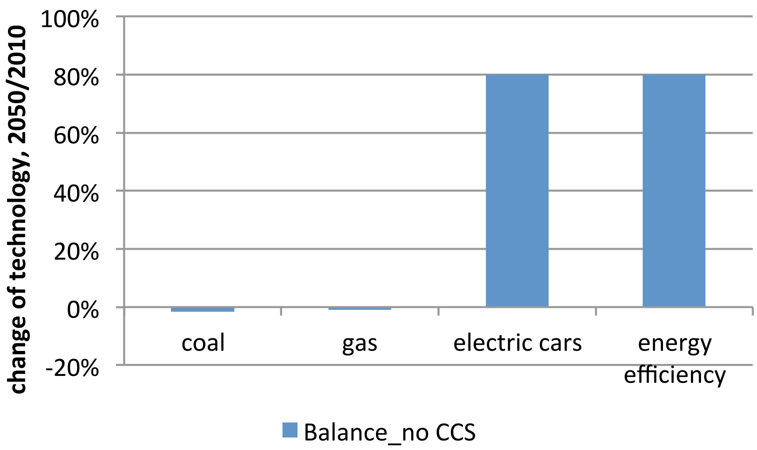

Fig.13. Technology roadmaps by balanced technology development in France in 2050 compared to 2010

The sensitivities of parameters in the roadmap above are presented in the table 7. 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.7. Sensitivity of parameters by balanced technology development on the CO_2 emissions in France

Δ(-1%)	e_{coal}	e_{oil}	e_{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. 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_2 emissions even though the share of coal in the energy mix is very small.

4.3. Technology roadmaps in the United States

In the US, 43% of the CO_2 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_2 emissions in 2010. According to the government policy, the CO_2 emissions will be reduced by 82% compared to 2010 level. Its technology pathways in the policy scenario are shown in the figure 14 without CCS and in the figure 15 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%.

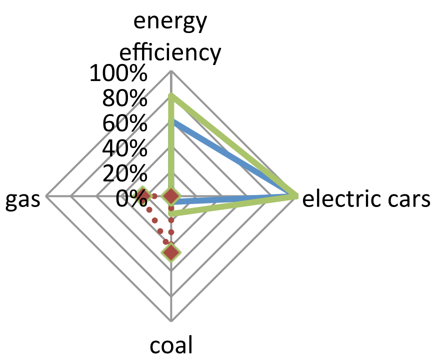

Fig.14. Technology roadmaps without CCS in the US

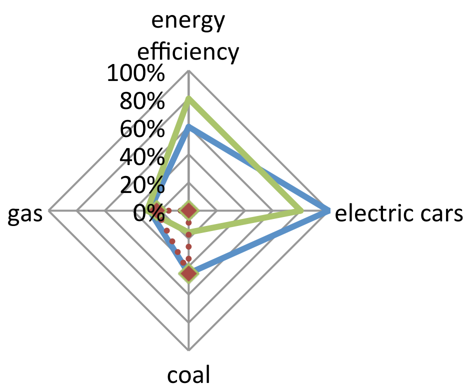

Fig.15. Technology roadmaps with CCS in the US

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%.

The roadmaps are based on two criteria: one with balanced CO_2 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.

1) Balanced technology development roadmaps for the United States

In the US, the power sector and transport sector are two most important sectors for CO_2 emissions, which account for respectively 43% and 30% of total emissions in 2010.

The figure 16 show the technology roadmaps with balanced technology development across sectors with and without CCS. If CCS is not considered in the energy transition in the US, 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%.

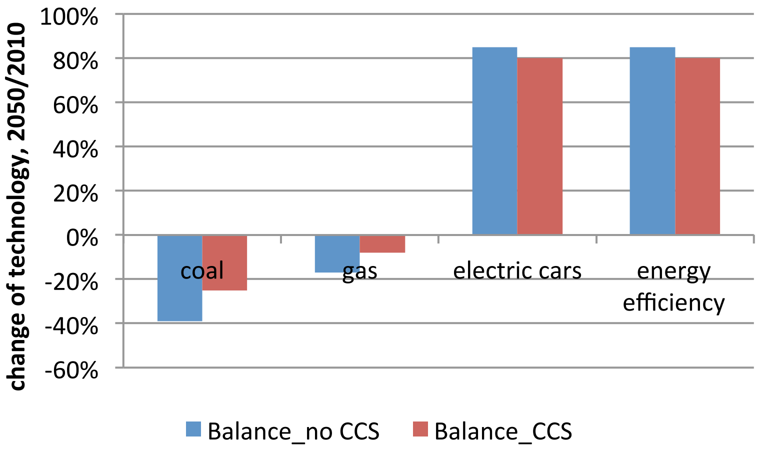

Fig.16. Technology roadmaps by balanced technology development in the US in 2050 compared to 2010

The sensitivities of parameters are shown in the table 8. 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 sensiblity 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.8. Sensitivity of parameters by balanced technology development on the CO_2 emissions in the US

Δ(-1%)	e_{coal}	e_{oil}	e_{gas}	Car number	Electricity output
Balance_no CCS	-0.2468%	-0.0206%	-0.0617%	-0.0159%	-0.3131%
Balance_CCS	-0.0820%	-0.0021%	-0.0154%	-0.0045%	-0.0949%

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 17. 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%.

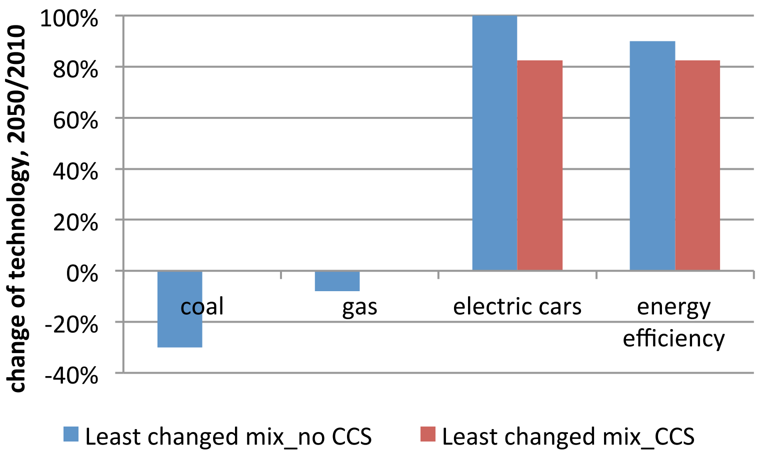

Fig.17. Technology roadmaps by least changed energy mix in the US in 2050 compared to 2010

The sensitivities of parameters in the technology roadmaps by least changed energy mix are shown in the table 9. 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 sensiblity 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.9. Sensitivity of parameters by least changed energy mix on the CO_2 emissions in the US

Δ(-1%)	e_{coal}	e_{oil}	e_{gas}	Car number	Electricity output
Least changed energy mix _no CCS	-0.6222%	-0.0207%	-0.1555%	-0.0451%	-0.7534%
Least changed energy mix _CCS	-0.1848%	-0.0021%	-0.0236%	-0.0099%	-0.2006%

In brief, the governmental target of reducing CO_2 emissions is very severe. 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_2 emissions.

5. Conclusion and discussion

In this article, a Sectoral Emission Model has been set up for CO_2 emissions; between 2010 and 2050; in China, France and the US, in order to assessing the governments targets for the CO_2 emission reductions. Our model provides a solution pool of energy roadmaps focusing on the main energy technologies: energy mix, electric vehicles, energy efficiency, and CCS. Our model shows that completely change of energy structure in all sectors is necessary to achieve the governmental reductions.

In China, half of the emission reductions are expected to be contributed by the power sector, as the power sector accouts for half the emissions in 2010. 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. Meanwhile, the energy efficiency should also be improved by 80% to reach the governmental target. As the power sector contributes little to the CO_2 emission, CCS is not a necessary option for France.

In the US, the reduction of emissions is divided homogenously across sectors as all the three sector have the same importance for the reduction of emissions. All sectors should make large effort (more than 80% of emissions should be reduced) in order to reduce CO_2 emissions. Same as China, if the energy mix is expected to be kept unchanged, then CCS should be implemented.

The tests of sensitivities of parameters in our Sectoral Emission Model for different technology roadmaps, in the different countries, show that the electricity output and the emission intensity of production are the two parameters with the most important sensitivity on CO_2 emissions: improving the efficiency of coal combustion will play the leading role in the emission reductions.

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