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

Pascal da Costa¹, Wenhui Tian²
July 21, 2014

Abstract: In order to avoid dangerous climate change, the Intergovernmental Panel on Climate Change has suggested that the increase in global temperature should be limited to under 2°C by the end of this century. In response to this objective, many countries have set up varied mitigation targets for CO₂ emissions, which reflect their own specific situations. In this article, scenarios for CO₂ emissions up to 2050 are set up for three representative countries: the United States of America, France and China. We compare these scenarios to Business-as-Usual scenarios in the framework of a sectoral-emission model. This model establishes the feasibility of the scenarios and targets, by dividing emissions into three main sectors: the power sector, the transport sector and others. The model, based on STIRPAT modeling and Support Vector Regressions, includes three major types of technical improvements: hybrid vehicles, energy-structure changes and energy-efficiency improvements.

Governmental targets prove to be stricter than the 2°C scenario for the US and France, while the governmental target for China is more tolerant than the 2°C scenario, taking economic development into account. The article also shows that the energy mix could remain unchanged for electricity production with the implementation of Carbon Capture and Storage technology in order to hit the government target in China, and the 2°C objective in the US. Otherwise, these countries would have to reduce their share of coal in the energy mix to under 20%. In the meantime, half of traditional vehicles should be replaced by hybrid vehicles, and energy efficiency has to be improved by over 50% to achieve the targets of all the three countries.

JEL Codes: Q47; Q54. **Keywords:** STIRPAT Model; Support Vector Regression; CO₂-Emission Scenarios.

1. Introduction

The world's economic development will undoubtedly require greater energy production. This greater energy demand will inevitably put pressure on both natural resources and the climate. It is however difficult to exactly forecast future energy use, as this depends on many unpredictable factors, such as energy prices, energy policies, demographic change, economic growth and technical change. Despite these uncertainties, energy projections are primarily based on historical data. Projections may obviously often be inaccurate if they do not include information on future changes. In this context, various qualitative energy scenarios should be analyzed, in order to identify the main driving forces. It is in this light that the Intergovernmental Panel on Climate Change has developed contrasting scenarios for CO₂ emissions, growth, the behavior of economic agents, etc. (IPCC, 2014).

The macroeconomic modeling of energy and climate is now more often applied in this direction. However, a number of families of applied models continue to co-exist, each markedly different in terms of their decompositions (sectoral, regional, fiscal, etc.), theories (endogenous or exogenous growth, market structures, etc.) and long- or mid-term perspectives (Chen, 2005; Brécard et al., 2006; Klaassen and Riahi, 2007; Saveyn et al., 2012). The mechanisms and assumptions behind these existing applied economic models are often contradictory, which makes it difficult to compare their results and understand the numerous differences in predictions (Boulanger and Bréchet, 2005).

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In this article, we propose a less complex (less data, simple framework, etc.) but complementary approach: a sectoral-emission model for three country types that may be considered to represent a number of other similar countries in the world. China (CN) is a fast-emerging economy characterized by rising energy consumption. France (FR) is a well-developed economy with relatively low CO₂ emissions. And the United States of America (US) is both the largest economy and a major source of emissions.

The sectoral-emission model is proposed to check the scientific relevance and feasibility of the CO₂-emission scenarios with respect to the economy and CO₂ emissions over the coming 40 years. Our model has three sectors: electricity-generation, transport, and others. These are considered separately as the power and transport sectors are the main sources of CO₂ emissions. Energy structure, Carbon Capture and Storage (CCS), electric vehicles and energy efficiency are the key parameters in reducing CO₂ emissions. In this context, we here attempt to uncover the right measures to match the scenarios we set out in order to reach the government targets.

We employ two methodologies to make robust projections from available historical data. The first is the Stochastic Impacts by Regression on Population Affluence and Technology (STIRPAT) model, which helps to simulate the Business-as-Usual scenarios for CO₂ emissions by country. Second, for future electricity production, we appeal to Support Vector Regressions (SVR). We can calculate the evolution of both electricity mix and energy technology use for each country.

The model shows that the government targets in France and the US seem to be very strict, considering country characteristics and the range of future likely evolutions. Their attainment will thus require drastic innovations and major improvements covering many aspects. The government targets which are announced in the US and France are even more stringent than the IPCC's objectives. In China, a fast-developing country, emissions will fall sharply as it develops. Therefore the Chinese government targets can be more ambitious, since they are currently less stringent than the IPCC objective, and thus enter into the 'realm of the possible'.

The remainder of the paper is organized as follows. Section 2 presents the CO₂-emission scenarios. Section 3 sets out the sectoral-emissions model, and the results are discussed in Section 4. Last, Section 5 concludes.

2. The CO₂-Emission Scenarios

Organizations such as the International Energy Agency (IEA), the United States Energy Information Administration, the World Energy Council and so on have proposed different energy scenarios. Considering the differences between our three countries, US, FR and CH, we have modified the assumptions made by the IEA (2008) as follows: we adopt the STIRPAT model to simulate the relationship between CO₂ emissions and the economic and demographic variables.

The STIRPAT model is derived from the IPAT identity by Ehrlich and Holdren (1971):

$$\text{Impact } I = \text{Population} \times \text{Affluence} \times \text{Technology} = P \times A \times T \quad (1)$$

Analytically, the IPAT identity describes the multiplicative contribution of population (P), affluence (A), and technology (T) to environmental impact (I). In the current article, environmental impact (I) is CO₂ emissions; population (P) refers to the size of the human population; affluence (A) income per capita; and technology (T) CO₂ emissions per unit of GDP (or CO₂-intensity).

The STIRPAT model is developed based on the IPAT identity, allowing the factors to have different influences on the environment (Dietz and Rosa, 1994). The STIRPAT technique statistically models the non-proportional impact of variables on the environment (Dietz and Rosa, 1997; Lin et al., 2009; Martínez-Zarzoso and Maruotti, 2011; Meng et al., 2012; Squalli, 2010; Wei, 2011; York et al., 2003). The STIRPAT equation is:

$$I_i = a * P_i^b * A_i^c * T_i^d * e_i \quad (2)$$

where I , P , A , T represent the same variables as in the IPAT identity (1); i indicates the time series; a defines the scale of the model; b , c , and d are the exponentials of P , A and T respectively; and e is the error term.³

We use data from 1971 to 2010 (IEA, 2012) to predict the Business-as-Usual scenario up to to 2050. We retain four types of scenario in our analysis:

- i. **The Business-as-Usual (BaU) scenario.** Here the data are derived from the STIRPAT model. CO₂ emissions in China will reach 18207mt in 2050, a 2.5-fold increase over 2010. The analogous figures are 261mt (73%) in France and 8662mt (1.6-fold) in the US. More details are provided in Appendix B.
- ii. **The Accelerated Technology (ACT) scenario.** Here the future values are determined by criteria which vary according to the country's development level. According to the IEA, under the ACT scenario emissions in 2050 should fall back to their 2005 level. This assumption works for China, but turns out not to be applicable for France and the US. Under this assumption, 2050 emissions are set to be 0.65 times their 2005 level in France, and 0.75 times their 2005 level in the US.
- iii. **The 2°C scenario.** In this case, CO₂ emissions will be halved by 2050 relative to their 1990 levels. This scenario reflects the ambitious objectives of IPCC in order to limit global warming to just 2°C.
- iv. **The government target scenario.** In 2009, China promised to reduce its CO₂ intensity (CO₂ emissions per unit of GDP) by 40%-45% by 2020 (ERI, 2009), with this objective being extended to 85%-90% by 2050; the US planned to reduce their CO₂ emissions by 17% in 2020, and by 83% in 2050 (Waxman and Markey, 2009); and the French government announced a reduction of CO₂ emissions by 75% by 2050 compared to their 2005 level (IEA, 2009).

Using PWC (2011) for the projections of GDP over the next 40 years, we have two government-target scenarios for China: a 40% intensity scenario and a 45% intensity scenario. All of the scenarios for these three countries are illustrated in the following figures:

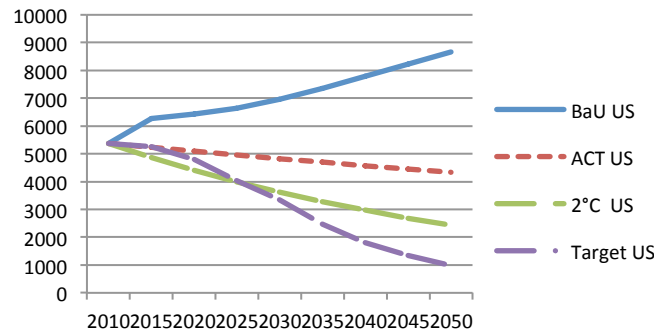


Fig. 1. CO₂-emission scenarios and the US target, 2010-2050 (mt)

³ If $a = b = c = d = e = 1$, the STIRPAT reduces to the IPAT identity (York et al. 2003) and T is included in the error term (unlike in the IPAT identity, where T serves to balance the equation).

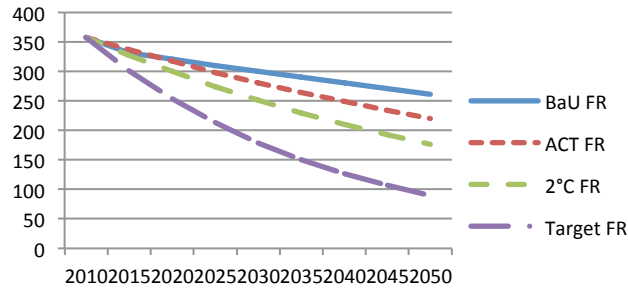


Fig. 2. CO₂-emission scenarios and the French target, 2010-2050 (mt)

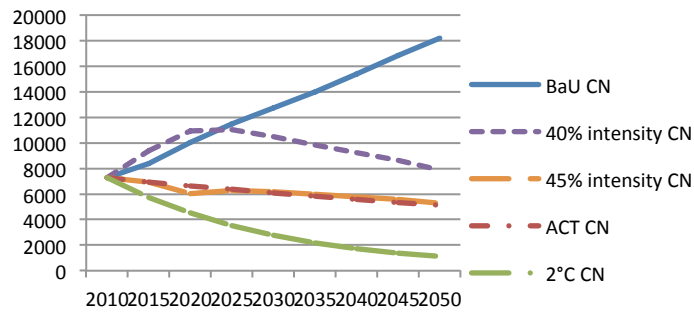


Fig. 3. CO₂-emission scenarios and the Chinese target, 2010-2050 (mt)

These figures shows that CO₂ emissions will continue to rise in China and in United States under the BaU scenario. Under the ACT scenario, CO₂ emissions will fall at the same rate in France and China, while this rate is much lower in the United States. In order to limit the temperature rise below 2°C, emissions should be reduced at an annual rate of 1.76% in France and 1.95% in the United States, while China needs to make a greater effort with a fall of 4.56% per year. The government targets for both the United States and France are much stricter than the other scenarios. However, Chinese emissions are hump-shaped: CO₂ emissions will peak at around 2030 and then progressively fall with the 40% intensity target. The 45% intensity target is quite similar to the ACT scenario. Under the 40% intensity target, peak emissions in 2030 are equal to the emissions in the BaU scenario, but emissions in 2050 are 44.4% of those in the BaU scenario. Emissions with the two targets vary from 28% to 43% of the BaU scenario in 2050, which is 4.5 to 7-times those under the 2°C scenario.

3. The Sectoral-Emission Model

We analyze the composition of CO₂ emissions by dividing CO₂ sources into three sectors: electricity generation; transport; and other sectors, which include industry and domestic.

Figure 4 below shows the CO₂-emission shares of the three sectors in 2010. The primary source of CO₂ in the United States and China is electricity generation, accounting for 43.0% and 49.3% of total emissions respectively. The transport sector represents one third of all emissions in France, which is twice the figure for the power sector, due to nuclear energy.

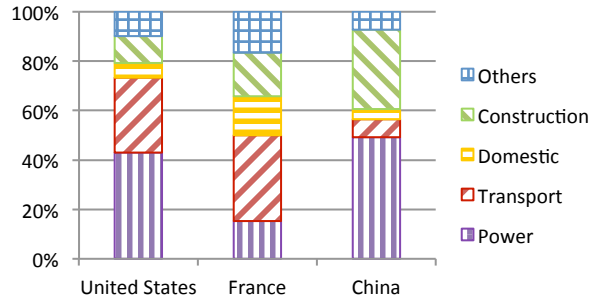


Fig. 4. Sectoral-emission shares in 2010 (IEA, 2012)

We thus principally analyze the power and transport sectors here, in which fuel mix, CCS and hybrid vehicles are three key factors behind CO₂ emissions. Improved energy efficiency in the domestic sector also contributes to CO₂-emission mitigation. CO₂ emissions can be written as:

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

where $E_{(t)}$ is total CO₂ emissions in year t , and $E_{P(t)}$, $E_{T(t)}$ and $E_{R(t)}$ are CO₂ emissions in the power, transport and other sectors in year t .

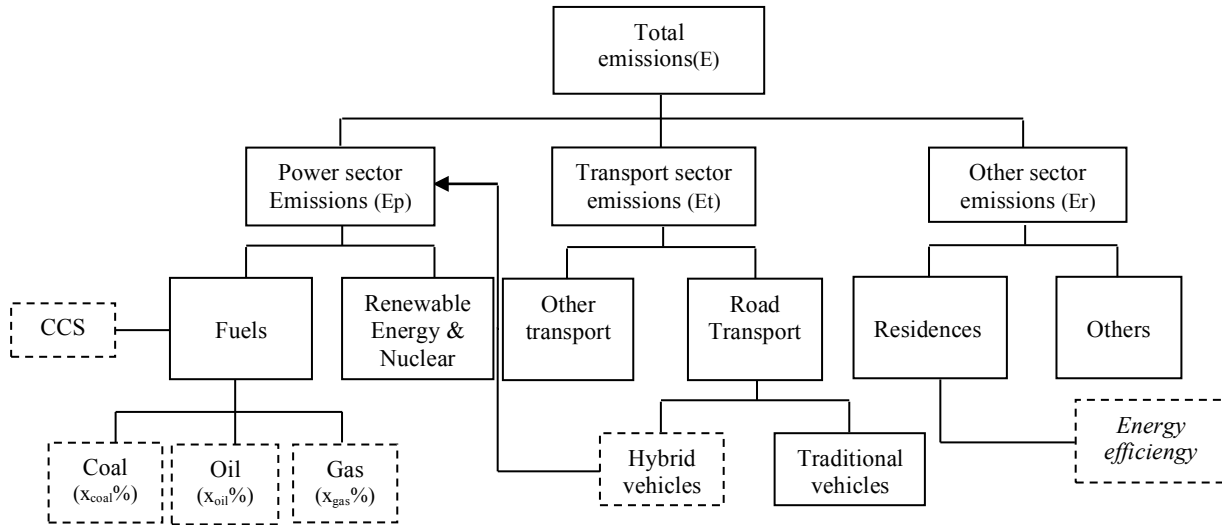


Fig. 5. Schema of the sectoral-emission model

The structure of the sectoral-emission model is presented in the schema above (Fig. 5): the factors in dotted boxes are those considered in the model.

3.1. The Power-Generation Sector

As a result of the different energy structures in the power sector, CO₂ emissions per KWh from electricity generation vary greatly across countries. The following figures show that CO₂ emissions per KWh in France have been only 12% of the Chinese level and 20% of the US level over the past twenty years, as coal plays a dominant role in China and the US, while nuclear power plants currently account for 80% of French electricity output.

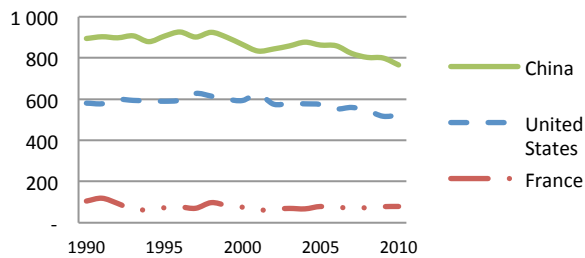


Fig. 6. CO₂ emissions per KWh from electricity generation, gram /KWh (IEA, 2012)

China has abundant coal reserves, while its oil, natural gas and other fossil energy resources are limited. Coal is currently the dominant power fuel. At the end of 2010, thermal power accounted for 73.4% of total power-generation capacity (IEA, 2011c). Without some very significant technology breakthrough in power generation, coal-fired power is expected to remain the main source of electricity over the coming 40 years. At the same time, hydropower, nuclear power, and wind and solar power will become increasingly important, with natural-gas generation serving as a supplementary power source. Up to 2030, coal generation and hydropower capacity will steadily increase. In 2050, power-generation technologies will be more efficient and diversified, and coal-fired electricity's share of total installed capacity will fall to 35%. China's final power consumption is likely to reach 8 000 TWh by 2020, 10 000 TWh by 2030 and 13 000 TWh by 2050 (IEA, 2011a, c).

The Chinese government has also proposed a “low-carbon development strategy” in order to meet increasing energy demand over the next 40 years. For example, as the “China Wind Energy Development Map 2050” (IEA, 2011c) foresees, total installed wind-power capacity will represent 5% of total electricity production by 2020. By 2030, wind power will account for 8.4% of total electric power consumption and 15% of total electric power capacity. Wind power will thus play an increasing role in meeting China's electricity demand, improving its energy structure and supporting its economic and social development. By 2050, installed capacity could reach 1TW, about 26% of total power capacity, and wind power will cover 17% of the national power supply. Using information from the IEA (IEA, 2011a), the historical power structure over the past 30 years in China is presented in Figure 7.

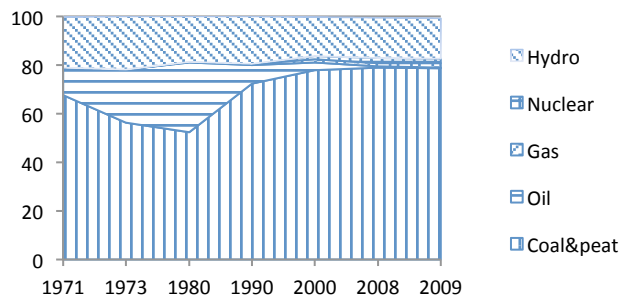


Fig. 7. The share of electricity generation from fuel sources in CN, 1971-2009 (IEA, 2012)

France is one of the least CO₂-intensive industrialized economies. CO₂ emissions have been declining since 2005 from an already relatively low base. By 2007, France had reduced its total CO₂ emissions below its Kyoto target. In 2009, nuclear power accounted for 76.24% of France's electricity generation and over 40% of total primary energy supply (TPES). France imports nearly all of its oil, gas and coal requirements, but its fossil-fuel imports are well diversified. The current share of gas in

TPES in France is low compared with other IEA European countries. In 2008, natural gas accounted for nearly 15% of TPES, up from 12% in 1990, but still well below the IEA European average of 25%.

Under the BaU scenario, the French government projects that the share of gas in the power sector will increase from under 4% currently to over 10% in 2020. Oil use for power generation is minimal and accounts for only 1.1% of total electricity generation. The final demand for oil represents some 93% of oil TPES, and the transport sector accounts for over half of final oil demand. The share of renewable energy in electricity production in 2007 was 12%, with hydropower accounting for over 85% of this figure. The following figure depicts the shares of the main sources of electricity generation over the past 40 years using IEA data (IEA, 2011c):

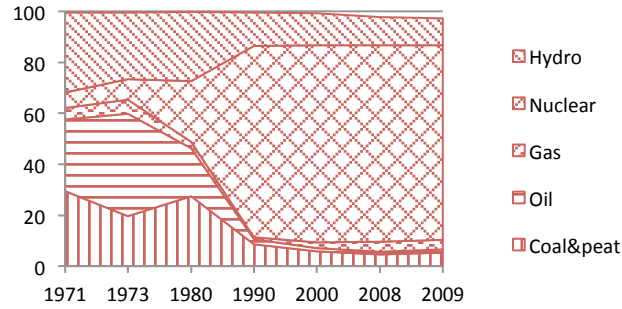


Fig. 8. The share of electricity generation from fuel sources in FR, 1971-2009 (IEA, 2012)

The United States depends on fossil fuels for almost all its energy supply. Natural gas use is rapidly growing in the US, in particular in power generation, where it has now overtaken nuclear to become the second most important power-generation fuel. Coal is also an important fuel in the United States, accounting for half of the country's electricity generation, and contributing in particular to the economies of the Western states. CO₂ emissions in the US rose by 16% between 1990 and 2005. The most significant sector for CO₂ emissions is electricity generation, accounting for 41% of total energy-related CO₂ emissions in 2005, followed by transport, which accounted for 33%. The shares of the main energy sources for power generation are depicted in Figure 9 using IEA data (IEA, 2011b).

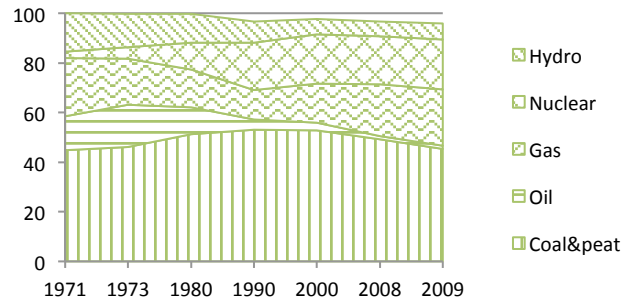


Fig. 9. The share of electricity generation from fuel sources in US, 1971-2009 (IEA, 2012)

Fuels such as coal, oil and gas contribute to CO₂ emissions in the power sector; analytically, emissions in year t are divided into these three categories as follows:

$$E_{P(t)} = Q_t * \sum x_{i,t} * e_{i,t} \quad (4)$$

where Q_t is electricity output in year t , x_i represents the three main fuels: coal, oil and natural gas; equally e_i represents the CO₂ emissions from using coal, oil and gas respectively.

CO₂ emissions per KWh (the emission intensity) of each fuel vary widely between countries according to the different types of energy and technology levels. The emission intensities of fuels are

the lowest in Europe, so we adopt the emission intensities in 2010 of Europe as the intensities for the three countries in 2050, which are e_{coal} 0.8kg/kwh, e_{oil} 0.4kg/kwh, and e_{gas} 0.2kg/kwh.

As for electricity production, we set up a model with the Support Vector Machine (SVM) of the historical data over the past 40 years for more robust prediction.⁴ The electricity-production simulation results are based on 1971-2010 data (IEA, 2012). Chinese electricity output will be 10248TWh in 2050, a 2.43-fold rise over 2010. In France it will be 539TWh in 2050, a 4% fall from 2010, and 4785TWh (a 10% rise over 2010) in the United States (see Appendix C).

3.2.The Transport Sector

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 “World Economic Outlook” (IEA, 2011).

The transport sector is responsible for the largest share of CO₂ 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 is able to reduce transport emissions by focusing on electricity-based technologies, such as high-speed rail and electric vehicles. The 2015 goal of the French electric-vehicle roadmap is to reach 10% penetration of new vehicle sales. The 2020 goal is 7% of the total vehicle stock (IEA, 2009).

In 2010, the US had the most cars of any country in the world (254 million), with transport accounting for 30% of CO₂ emissions, of which road emission was responsible for 86.4%. In China, transport accounts for only 7% of total 2010 emissions. With a growth rate in the number of cars of 11% in 2010, transport, and especially road transport, will be increasingly important for future CO₂ emissions.

In this context, the mitigation of CO₂ emissions is critical for the road transport sector. Besides improving energy efficiency, the use of hybrid vehicles can also reduce fuel consumption. With current technology, a hybrid vehicle consumes 0.01~0.03 KWh/km. In this paper, we employ the mean value of 0.02 KWh/km, that is 7.3MWh per year, which makes a notable contribution to total electricity output.

The CO₂ emissions of the transport sector in year t are then calculated as:

$$E_{T(t)} = \frac{E_{\text{road}(t)}}{\alpha_{\text{road}}} = \frac{E_{\text{road}(2010)} * (1+\gamma)^t * (1-0.5*y_t)}{\alpha_{\text{road}}} \quad (5)$$

where $E_{T(t)}$ are CO₂ emissions in the transport sector in year t , $E_{\text{road}(t)}$ are CO₂ 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 CO₂ emissions of the transport sector.

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

$$E_p^{tr} = 7.3 * y_t * N_{(t)} \quad (6)$$

where $N_{(t)}$ is the stock of vehicles in year t . Total electricity output is therefore: $E_{P(t)} + E_p^{tr}$.

3.3.The Domestic Sector

Amongst the “other” sectors, we consider primarily domestic consumption. In 2010, domestic CO₂ emissions accounted for 22.4% of those in the other sectors in the United States; in France and China, this figure was 31.8% and 9.6% respectively. Domestic energy consumption can be reduced by improving energy efficiency. Domestic CO₂ emissions are then written as follows:

⁴ More details about SVM models and the toolbox devoted to SVR can be found in Appendix A. In our work here, the data sets are all normalized from the raw data. We use a sigmoid kernel function for electricity-production prediction.

$$E_{R(t)} = \frac{E_{Rr(t)}}{\beta} = \frac{(1-e)*E_{Rr(baseline)}}{\beta} \quad (7)$$

where $E_{R(t)}$ is CO₂ emissions from the other sectors in year t , $E_{Rr(t)}$ is domestic CO₂ emission, e is domestic-energy efficiency, $E_{Rr(baseline)}$ is domestic CO₂ emission without taking energy efficiency into account, and β is the domestic share in other sector CO₂ emissions.

4. Results

Figures 10 to 13 reveal the possible solutions for the scenarios and government targets, in the three sectors.⁵ Under the 2°C scenario and government target scenarios, we propose two technical possibilities for the power sector: one ‘with CCS implementation’, the other ‘without CCS’. The CCS technology can theoretically capture up to 90% of CO₂ emissions from a power plant or industrial facility and store them in underground geologic formations. But this technology is relatively expensive, from the data in 2002 (Rubin, 2006), the cost ranges between 15~75\$/tCO₂ for the capture from a coal- or gas-fired power plant, and storage in the ocean is 5-30\$/tCO₂. As such, the total cost of CCS is 10-500 billion \$ for the United States, 7-35 billion \$ for France and 130 -720 billion \$ for China.

In the electricity-generation sector, the US and China depend mostly on coal and gas, while in France nuclear plants do not much affect CO₂ emissions. In 2010, the share of coal, oil and gas in electricity production was respectively 45%, 1% and 23% for the US, 5.3%, 1.2%, and 3.9% for France, and 78.7%, 0.4% and 17% in China. However, in the BaU scenario, the utilization of coal could replace the other fuels and clean energies in the US and China (Fig.10). Compared to 2010, the United States will have to reduce fuel combustion by a half under the 2°C scenario, without CCS. Otherwise, CCS must be installed to keep the fuel mix unchanged. For China, in order to achieve the 2°C scenario, nearly all fuel combustion should be abandoned and replaced by clean energy without CCS implementation. With CCS, the fuel share could be at the same level as that under the ACT scenario. In order to reduce US emissions by 83%, electricity generation with coal should fall by 75%, and gas utilization should be reduced by a half, without CCS. This target could be achieved with the help of CCS by reducing coal combustion by only 50%. For China’s target of reducing CO₂ intensity by 45%, coal combustion should fall by 65% without CCS, and 20% with CCS. Figures 10 and 11 show the shares of coal and natural gas under different scenarios for these three countries.

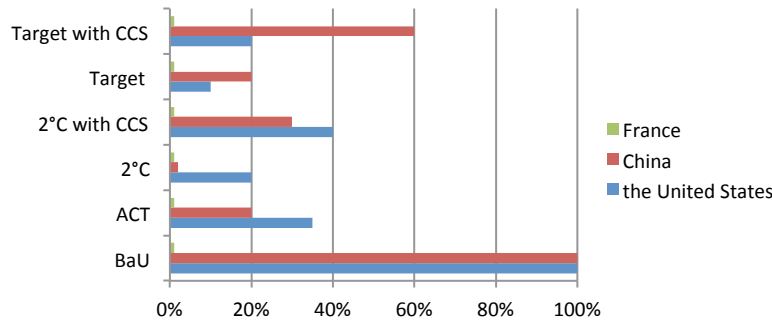


Fig. 10. Share of coal in the power production sector, 2050

⁵ In order to make a simple and clear comparison, we choose only the 45% target for China.

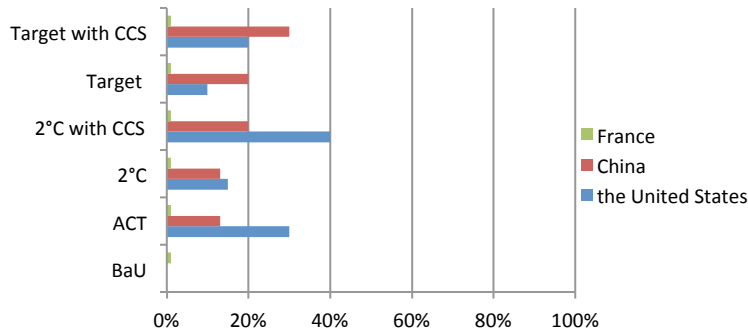


Fig. 11. Combustion of gas in the power production sector, 2050

For the transportation sector in the US, we suggest that 90% of cars (80% with CCS) be converted into hybrid vehicles to meet the government’s low-emission target. This reflects the large number of cars in the United States. There are fewer cars in France than in the US, but still 80% of them should be converted into hybrid vehicles to attain the government target and 55% for the 2°C scenario, as their emissions account for one third of all emissions. Last, in China the use of hybrid vehicles should be 70% for the government target (50% with CCS), or 100% (90% with CCS) for the 2°C scenario.

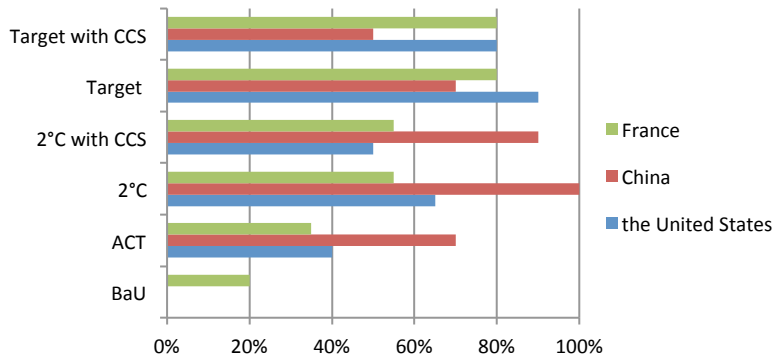


Fig. 12. Employment of hybrid vehicles, 2050

In the domestic sector, energy efficiency should be improved by 90% in the US, 70% in France and 60% in China to meet the governments’ targets without CCS. In the 2°C scenario, energy efficiency is planned to increase by 60% in the US, 50% in France and 90% in China without CCS. The large rise in energy efficiency is difficult, as it requires improvement in many respects, such as building insulation, and heating/cooling systems.

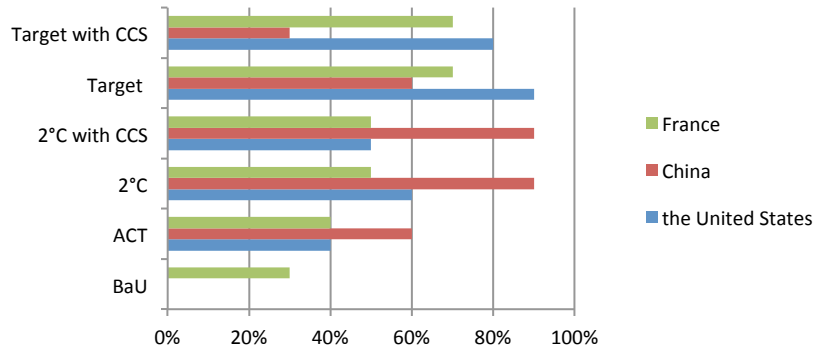


Fig. 13. Improvement of energy efficiency in housing, 2050

5. Conclusion

At the Copenhagen Summit on Climatic Change (2009), many countries promised new reduction targets for CO₂ emissions up to 2050. These reflected their own particular situations, mainly regarding population changes, economic growth and technological developments. In this article, our sectoral-emission model has been set up for CO₂ emissions over the next 40 years in the United States, France and China, with three scenarios and one government target. This model is proposed in order to test the feasibility of governmental targets, compared to the climatic objectives of the scientific community. By decomposing CO₂ emissions into three sectors (electricity generation, transport, and other sectors), we conclude that the government targets for France and the United States prove to be quite strict. Hitting governmental targets would require huge improvements in many aspects without advanced technology, such as CCS. While for China, the 2°C scenario is the toughest scenario, because it will need a complete change in energy structure over all sectors with current technologies.

CO₂ emissions will definitely fall over the coming 40 years, but in order to obtain the best climatic results, more research effort and R-D expenditures need to be mobilized in order to produce more advanced technologies and innovation: in power-generation and car emissions, especially in the United States and China; in renewable energy resources, again in China and the United States, in order to reduce the fossil-fuel share. These are the key areas that should be further supported in the future to reduce emissions, as they need to be. This support could be achieved by means of new fiscal incentives that are often absent today. For example the optimal carbon tax is often proposed (Grimaud et al., 2011; Acemoglu et al., 2012; Henriët et al., 2014) for its effects on both climate and endogenous innovation. This could be an interesting extension of our model and a way of expressing the costs of the different scenarios of CO₂ mitigations that were tested here.

References

- Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D., 2012. The Environment and Directed Technical Change. *American Economic Review* 102(1),131-166.
- Boulanger, P.-M., Bréchet, T., 2005. Models for policy-making in sustainable development: The state of the art and perspectives for research. *Ecological Economics* 55, 337-350.
- Brécard, D., Fougeyrollas, A., Le Mouél, P., Lemiale, L., Zagamé, P., 2006. Macro-economic consequences of European research policy: Prospects of the Nemesis model in the year 2030. *Research Policy* 35, 910-924.
- Cao, L., 2003. Support vector machines experts for time series forecasting. *Neurocomputing* 51, 321-339.
- Chen, W., 2005. The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling. *Energy Policy* 33, 885-896.
- Cortes, C., Vapnik, V., 1995. Support-vector networks. *Machine learning* 20, 273-297.
- Dietz, T., Rosa, E.A., 1994. Rethinking the environmental impacts of population, affluence and technology. *Human Ecology Review* 1, 277-300.
- Dietz, T., Rosa, E.A., 1997. Effects of population and affluence on CO₂ emissions. *Proceedings of the National Academy of Sciences* 94, 175-179.
- Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth. *Science* 171, 1212-1217.
- ERI, 2009. China's Low Carbon Development Path by 2050: Scenario analysis of Energy Demand and Carbon Emissions.
- Gao, J.B., Gunn, S.R., Harris, C.J., Brown, M., 2002. A probabilistic framework for SVM regression and error bar estimation. *Machine Learning* 46, 71-89.
- Grimaud, A., Lafforgue, G., Magné, B., 2011. Climate change mitigation options and directed technical change: A decentralized equilibrium analysis. *Resource and Energy Economics* 33, 938-962.

- Henriet, F., Maggiar, N., Schubert, K., 2014. A stylized applied energy-economy model for France. *Energy Journal*, *forthcoming*.
- Hong, W.-C., 2010. Application of chaotic ant swarm optimization in electric load forecasting. *Energy Policy* 38, 5830-5839.
- IEA, 2008. *Energy Technology Prospective 2008: Scenario & Strategies to 2050*.
- IEA, 2009. *Energy Policies of IEA Countries: France 2009 Review*.
- IEA, 2011a. *Energy Balances Non OECD 2011*.
- IEA, 2011b. *Energy Balances OECD 2011*.
- IEA, 2011c. *Technology Roadmaps: China Wind Energy Development Roadmap (2050)*.
- IEA, 2012. *CO2 Emission From Fuel Combustion HIGHLIGHTS*.
- IPCC, 2014. *Fifth Assessment Report*.
- Klaassen, G., Riahi, K., 2007. Internalizing externalities of electricity generation: An analysis with MESSAGE-MACRO. *Energy Policy* 35, 815-827.
- Lin, S., Zhao, D., Marinova, D., 2009. Analysis of the environmental impact of China based on STIRPAT model. *Environmental Impact Assessment Review* 29, 341-347.
- Liu, J., Seraoui, R., Vitelli, V., Zio, E., 2013. Nuclear power plant components condition monitoring by probabilistic support vector machine. *Annals of Nuclear Energy* 56, 23-33.
- Martínez-Zarzoso, I., Maruotti, A., 2011. The impact of urbanization on CO2 emissions: Evidence from developing countries. *Ecological Economics* 70, 1344-1353.
- Meng, M., Niu, D., Shang, W., 2012. CO2 emissions and economic development: China's 12th five-year plan. *Energy Policy* 42, 468-475.
- PWC, 2011. *The World in 2050. The accelerating shift of global economic power: challenges and opportunities*.
- Rubin, E., 2006. *Technical Summary: Carbon Dioxide Capture and Storage*. IPCC.
- Saveyn, B., Paroussos, L., Ciscar, J.-C., 2012. Economic analysis of a low carbon path to 2050: A case for China, India and Japan. *Energy Economics* 34, Supplement 3, S451-S458.
- Squalli, J., 2010. An empirical assessment of US state-level immigration and environmental emissions. *Ecological Economics* 69, 1170-1175.
- Wang, J., Zhu, W., Zhang, W., Sun, D., 2009. A trend fixed on firstly and seasonal adjustment model combined with the [epsilon]-SVR for short-term forecasting of electricity demand. *Energy Policy* 37, 4901-4909.
- Waxman, H.A., Markey, E.J., 2009. *The American Clean Energy and Security Act of 2009*.
- Wei, T., 2011. What STIRPAT tells about effects of population and affluence on the environment? *Ecological Economics* 72, 70-74.
- York, R., Rosa, E.A., Dietz, T., 2003. STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics* 46, 351-365.

Appendix A: Non-linear regressions using the SVM model (Cortes and Vapnik, 1995)

The SV algorithm is a nonlinear generalization of the Generalized Portrait algorithm of the 1960s. The formulation of SVM embodies the Structural Risk Minimization principle, which has been shown to be superior to Empirical Risk Minimization. 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 (Gao et al., 2002). When SVM is used for regression (especially non-linear regression), it is called a Support Vector Regression (SVR). SVR can estimate the nonlinear relationship between the data and produces good results after mapping the input data into a high-dimensional Reproducing Kernel Hilbert Space (RKHS), as compared to other commonly-used techniques.

SVR 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). Based on these works, we used SVR to make predictions for electricity production. As there are only a few dozen data points in our analysis, SVR is a good model for small databases.

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).

Appendix B: CO₂ emissions in CN, FR and US

The prediction is carried out with the STIRPAT model and tested by ordinary least squares (OLS) regression, with the data from the *CO₂ emission from fuel combustion highlights* of IEA in 2011.

The parameters in the STIRPAT equation ($\log I = \text{constant} + b * (\log P) + c * (\log A)$) are presented in the following table:

Tab. B. Values of parameters in STIRPAT

	Constant	b	c	R ²
CN	-0.679 (-0.284)	0.6546 (1.648)	0.5688 (8.468 ^{***})	0.9755
FR	3.3813 (0.650)	-0.0672 (-0.056)	-0.3416 (-0.929)	0.4338
US	8.1599 (4.590 ^{***})	-1.0816 (-2.825 ^{**})	0.9319 (4.702 ^{***})	0.8647

t-statistics are in parentheses. ^{**} is the 0.001 significance level and ^{***} the 0 significance level.

Figures B.1 to B.3 show the logarithm of CO₂ emissions in the three countries between 1971 and 2050. The X-axis is in years and the Y-axis in millions of tons.

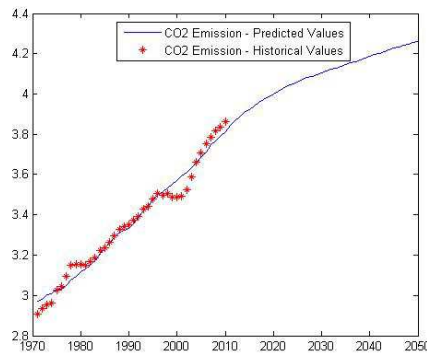


Figure B.1. The logarithm of CO₂ emissions in CN, 1971-2050

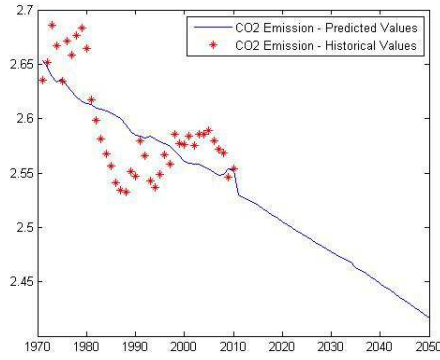


Figure B.2. The logarithm of CO₂ emissions in FR, 1971-2050

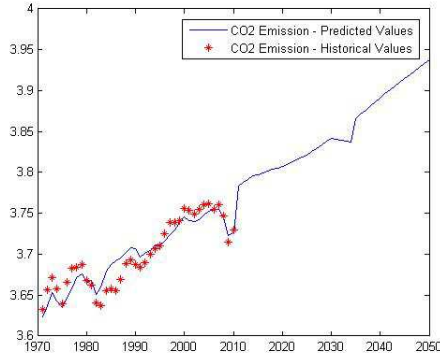


Figure B.3. The logarithm of CO₂ emissions in the US, 1971-2050

Appendix C: Electricity production in CN, FR and US

The Polynomial kernel Function $(\gamma * \vec{u} \cdot \vec{v} + \text{coef})^{\text{degree}}$ is used as the kernel function for electricity output by trial and error. The values of the related hyperparameters are also tuned with a Grid Search. The parameters are listed in the following table:

Table C. The values of the hyperparameters in electricity output

Item	C	degree	ξ	Υ	R^2
Output_CN	1	4	$1.0E^{-3}$	10	0.6478
Output_FR	1	4	$1.0E^{-3}$	10	0.7161
Output_US	1	4	$1.0E^{-3}$	10	0.7196

Figures C.1 to C.3 show electricity production in the three countries between 1971 and 2050. The predictions are carried out via a SVM model, using data from 1971 to 2010 from the *CO₂ emission from fuel combustion highlights* of the IEA in 2011. The X-axis is in years and the Y-axis in TWh.

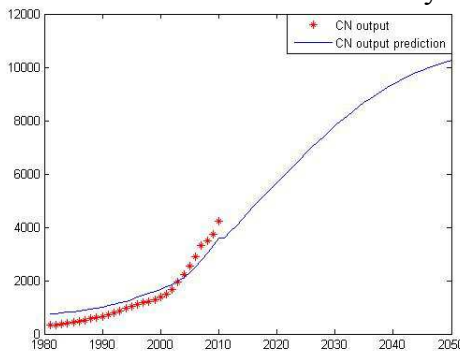


Fig.C.1. Electricity production in CN, 1981-2050

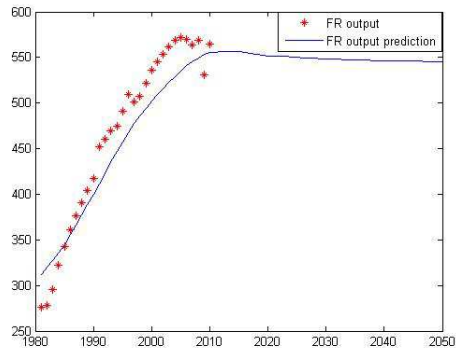


Fig.C.2. Electricity production in FR, 1981-2050

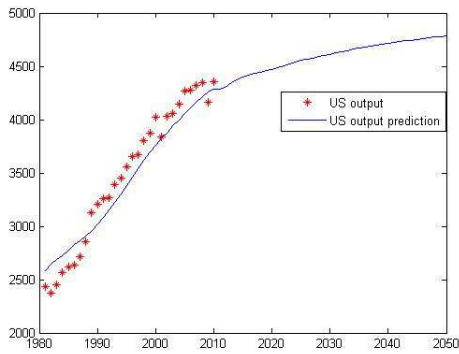


Fig.C.3. Electricity production in the US, 1981-2050