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Analysis of air pollution reduction and climate change mitigation in the industry sector of Yangtze River Delta in China

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ABSTRACT

China is now undergoing a fast process of industrialization, with the industry sector playing an important role in the overall economy. Among the many economic areas in China, Yangtze River Delta (YRD) takes the lead. The macro economy development and energy use status quo of both China and YRD are depicted, the past and current situation of air pollution and GHGs emissions is presented, and detailed national and local policies are reviewed. GAINS-China model is deployed in this study to evaluate the air pollution reduction and climate change mitigation achievements in the industry sector under the current policy of the three areas (i.e. Jiangsu, Zhejiang and Shanghai) in YRD from 2005 to 2030. According to the simulation results, the total population would grow marginally while the economy of YRD will keep booming in the next two decades. The total energy consumption of Jiangsu, Zhejiang and Shanghai in 2030 would be 2.36, 2.61 and 1.81 times that of 2005, with the industry sector still playing the biggest part. SO_2 emissions would be well under-control by 2030. The NO_X emissions all show steady growing trends, while the $PM_{2.5}$ emissions show different trends for three areas. The ensemble average years of life lost has a complex correlation with the total population and the $PM_{2.5}$ concentration. CO_2 emissions are still in predominant position among all the GHGs emissions, showing a steady growing trend towards 2030. All GHGs emissions amount in YRD would be 1.76 times that of 2005. The differences among the emissions in the three areas may due to reasons like economy scale, industrial composition, energy structure, and enforcement rate of policy. The uncertainties of this study may come from inaccurate prediction of scenario parameters and the expected policy changes in the future, and the emissions from the restructure of industry should be considered as well. In terms of achieving sustainable industrial development, YRD's governments should restrict the scale of energy-intensive industries, improve the primary energy structure, and take co-benefits concepts and methods more into policy-making processes.

1. Introduction

Despite the fact that most industrialized countries are now highly concerned about global warming and are making great efforts to cut down on their carbon emissions, less developed countries such as China and India are now right on their way of rapid industrialization and urbanization, which will be the predominant impetus for the global energy consumption in the coming decades. With a total population reaching 1.36 billion and the gross domestic products (GDP) reaching 9181.38 billion USD (7.7% more than 2012), China's urbanization rate has climbed up to a new level of 53.73%, by the end of 2013 (National Bureau of Statistics of China, 2014). To maintain the high speed of economic growth and social development, a great amount of energy, resources and materials have been consumed in China over the last decades. It is estimated that the primary energy consumption amount of China, by 2035, will almost match that of the OECD countries, and the CO_2 emissions will increase by 47% and account for 30% of world total, with per capita emissions overtaking the EU in 2017 and surpassing the OECD average in 2033 (BP, 2014a).

Although the proportion of the added value of tertiary industry (46.1%) in China has firstly exceeded that of second industry (43.9%) in 2013 (National Bureau of Statistics of China, 2014), the industry sector still holds the largest share (approximately 70%) in the

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energy consumption structure (Fig. 1) (National Bureau of Statistics of China, 2013) and remains the biggest contributor in terms of air pollutants emissions (Fig. 2) (National Bureau of Statistics of China and Ministry of Environmental Protection of China, 2013). Global climate change and local air pollution, two major issues which are usually studied and addressed separately, are actually closely related to each other, for greenhouse gases (CO_2, CH_4, N_2O, HFCs, etc.) and air pollutants (SO_2, NO_X, PM, VOCs, etc.) are emitted simultaneously from the combustion of fossil fuels, in spite of their temporal and spatial differences (Bollen et al., 2009a; Dulal et al., 2013). Even though it is projected that the coal share in China's primary energy consumption will decline from 69% (2012) to 52% (2035) with the highest renewables growth rate in the world (BP, 2014b), regarding the fact that China is still on the highway towards industrialization, the industry sector will still play as the biggest energy consumer among all the sectors. Therefore, China will be faced with increasing pressure to tackle the problem of air pollution reduction as well as climate change mitigation.

In response to the multiple challenges, China has adopted comprehensive strategies in terms of energy conservation, climate change mitigation, and air pollution control. *The Twelfth Five-Year Plan on Energy Development* is the blueprint to guide China's energy development during 2011–2015. It sets goals including at least 16% decline on energy intensity (i.e. the energy consumption amount per unit of GDP), and 17% decline on carbon emission intensity (i.e. CO_2 emission per unit of GDP), compared to that of 2010, as well as reducing NO_X and $PM_{2.5}$ concentration (The state council of the People's Republic of China, 2013a). *Twelfth Five-Year Plan on Greenhouse Gases Emissions Control* sets even more detailed reduction targets to different provinces and regions (The state council of the People's Republic of China, 2011). *Climate Change Adaptation Program of the Industry sector (2012–2020)* targets that the CO_2 emission per unit value-added of industry, in 2015 and 2020, would be 21% and 50% less than that of 2010, respectively (Ministry of Industry and Information Technology of China et al., 2012). *China's Policies and Actions for Addressing Climate Change (2013)* reviews China's efforts in 2013 on industrial structure adjusting, energy structure optimizing, energy conserving and forests carbon sinks increasing, etc. (National Development and Reform Commission of China, 2013). *Air Pollution Control Action Plan* sets the target that the PM_{10} concentration will drop by no less than 10% in 2017, compared to 2012, with Beijing–Tianjin–Hebei Area, Yangtze River Delta Area and Pearl River Delta Area decrease 25%, 20% and 15% respectively (The state council of the People's Republic of China, 2013b). *Twelfth Five-Year Plan on the Air Pollution Control of Key Areas* addresses the co-control measures of air pollutants in 13 key areas of China (Ministry of Environmental Protection et al., 2012). Determined to tackle the issue of both climate change and air pollution, China is now getting aware of achieving co-benefits by designing and implementing a smart mix of more cost-effective policies.

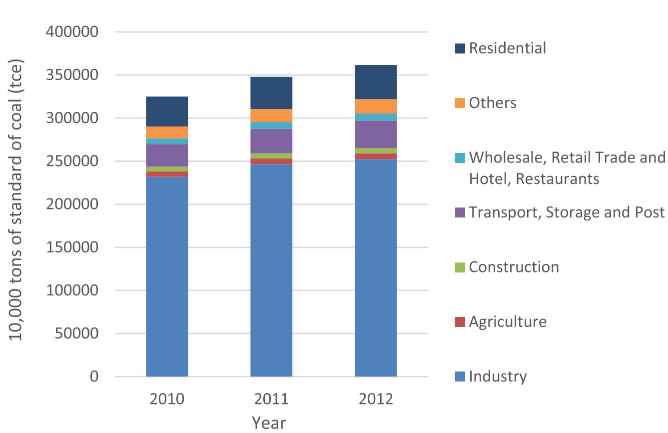

Fig. 1. Energy consumption amount and structure of China (by sector), 2010–2012.

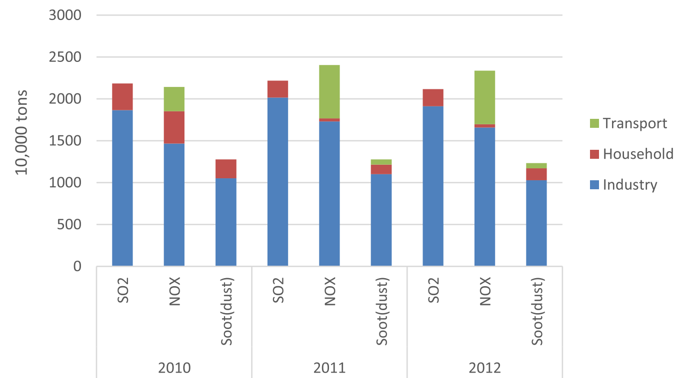

Fig. 2. Air pollutants emissions from different sectors of China, 2010–2012.

The study of co-benefits is becoming popular in recent years. Quite a few researches focus on finding out to what extent the co-benefits are brought about by certain interventions (laws, policies, programs, projects, etc.). Jiang et al. (2013) examined China's policies related to co-benefits in different sectors and selected two industrial areas as case studies to assess the co-benefits achieved by local mitigation measures. Oliveira et al. (2013) presented the magnitude of the co-benefits achieved by certain sectors in Asian cities. Ministry of the Environment of Japan (2009) has been making great efforts on promoting co-benefits approach and has developed a set of indicators and calculation equations to evaluate the co-benefits approach in terms of environmental projects such as CDM, by different categories. Relevant models are being utilized more frequently in co-benefits assessment as well. For instance, Geng et al. (2013) and Mao et al. (2012) used different models to project the carbon dioxide emission and air pollutants emission under different policy scenarios in the transport sector. Chen et al. (2006) forecasted the energy consumption and explored the co-benefits under 3 different energy policy scenarios in Shanghai by using MARKAL model. Xu and Toshihiko (2009) simulated the impacts on local air pollutant emission reduction and ancillary CO_2 emission reduction of SO_2 control policies in China based on AIM/CGE model. Bollen et al. (2009b) reviewed the literatures on the estimates of the co-benefits and then used the extended MERGE model to make a new estimate in a global scale. Markandya et al. (2009) compared the health benefits resulted from GHGs reduction measures in EU, India and China by adopting POLES model, GAINS model and a WHO recommended model. He et al. (2010) combined 4 models, i.e. an energy projection model (LEAP), an emission estimation model (TRACE-P), an air quality simulation model (CAMQ) and a health benefit evaluation model (BenMAP) to assess the co-benefits from China's energy policies. Cao et al. (2008) made an integrated modelling analysis after a thorough methodology review on all the top-down and bottom-up models that have been used in co-benefits estimation. All these aforementioned quantitative analysis, especially through modeling methods, is now gaining its significance for in-depth research on co-benefits approach.

Yangtze River Delta (YRD) is the largest economic zone in China, with its industry sector playing an important role in the national economy. The main purpose of this study is to assess the co-benefits of GHGs reduction and air pollution reduction in YRD's industry sector through the application of GAINS-model, so as to give feasible suggestions to local and national policy-makers.

2. Background of Yangtze River Delta

2.1. Overview of YRD

As the largest economic zone of China, YRD consists of two provinces (Jiangsu and Zhejiang) and one municipal city (Shanghai). These three areas lie in the estuary of Yangtze River, which covers only 2.2% of the land area of China whereas feeds 12% of the national population and produces 21% of the national GDP (National Bureau of Statistics of China, 2013). Table 1 presents detailed information for three areas. Economy has been booming at a high rate in YRD, especially the industrial economy, which facilitates the pace of urbanization and promotes the well-being of local people. In Shanghai, a more developed metropolis, the tertiary industry leads a dominant role in overall economy. However, in Jiangsu and Zhejiang, secondary industry still accounts for the biggest share of the total energy consumption, and contributes to economy growth in a slightly higher ratio than tertiary industry (Fig. 3 and Fig. 4).

Nevertheless, huge quantities of energy consumption, especially fossil fuel combustion, have brought about severe negative outcomes to local air quality and public health. The report issued in December 2013 shows that the air quality of 2013 was the worst in the past 52 years, and over 100 Chinese cities were trapped in smog and haze for a long period, including many cities in YRD (Epoch Times, 2013). Fig. 5 shows the average air pollution concentration in three areas in 2012. It can be clearly illustrated that for the three types of air pollutants, SO_2 concentration is far below the new national standard, which will come into force in 2016 (Ministry of Environmental Protection of China, 2012). This may result from the strict and long-term implementation of total SO_2 emission control policy of China, which dates back to 2002 (Ministry of Environmental Protection of China, 2002). While SO_2 control policies have been executed for over ten years, the control of NO_X has just essentially begun from 2010 (Ministry of Environmental Protection of China, 2010). Particulate Matter (PM) remains the biggest challenge, especially in recent years. Even though the concentration of SO_2 and NO_X could be kept under control, the average annual PM_{10} concentration of these three areas all surpassed the national standard, with Shanghai and Zhejiang exceeding marginally and Jiangsu more eminently.

The GHGs emission of YRD is also becoming serious, even if its local impact is not as direct as air pollution. Most GHGs and air pollutants come from the same sources (i.e. fossil fuels), and they are inherently correlated. But still, few local policies take co-benefits concept and co-control strategy of GHGs and air pollutants into consideration.

2.2. Local policy review

The industry sector accounts for a considerable share in China's national economy, and also contributes most in regional GDP composition among all the economic sectors of YRD. The main industries of YRD include electronic equipment manufacturing, transportation equipment manufacturing, electricity supply, ferrous metal smelting and processing, chemical materials and chemical products manufacturing, as well as light industry such as textile industry. There are some differences among the industrial structure of the three areas, but in whole they are quite alike.

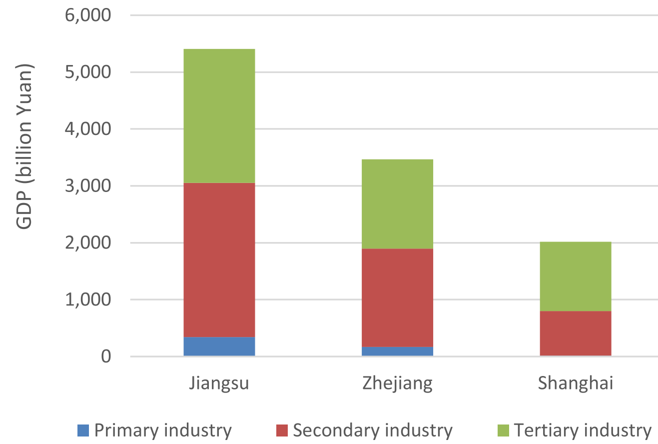

Fig. 3. Economic structure of YRD in 2012.

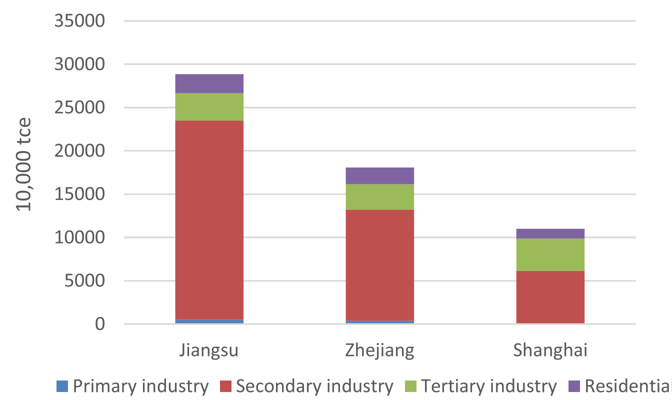

Fig. 4. Energy consumption of YRD in 2012.

Local policies on energy saving and environmental protection have been issued, in line with the national policies. Jiangsu province has issued a program on climate change mitigation within a decade (2010–2020), disintegrated the mitigation task into the city level, and started to establish the provincial greenhouse gases inventory. The carbon reduction target of per unit GDP has been incorporated into the assessment system of local government performance. A number of policies have been formulated on the prevention and control of air pollution, such as the *Blue Sky Project* and special schemes focusing on particle matter reduction (People's Government of Jiangsu Province, 2010, 2013).

Air Pollution Prevention and Control Action Plan of Zhejiang Province (2013–2017) was promulgated in the end of 2013, setting its goal of at least 20% fine particulate matter ($PM_{2.5}$) concentrations reduction in 2017 on the basis of 2012, by regulating on the total consumption amount of coal, promoting renewable energy development and so on. Zhejiang also issued programs on climate

Table 1
Key indicators of YRD in 2012.

Region	Area (10,000 km^2)	GDP (billion USD)	Population (10,000)	GDP per capita (USD)
Jiangsu	10.26	860.05	7920	10,874
Zhejiang	10.18	551.51	5477	10,083
Shanghai	0.63	321.08	2380	13,583

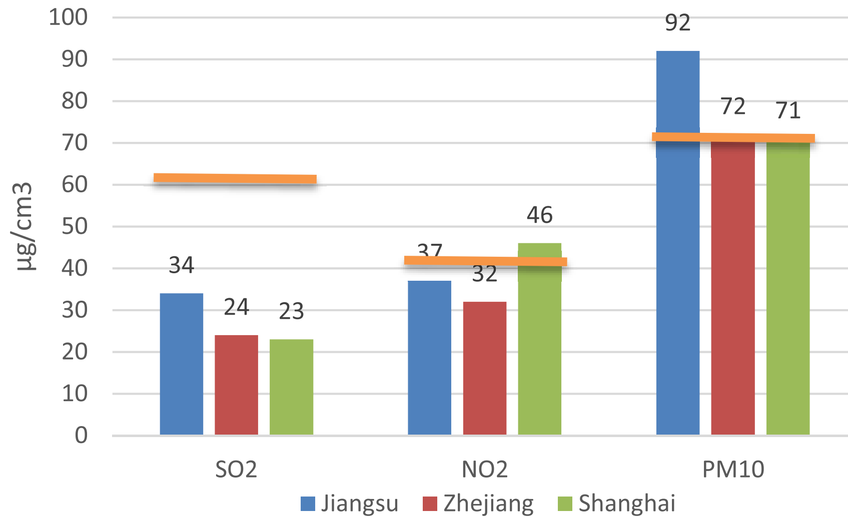

Fig. 5. Air pollutants emissions of YRD in 2012 (Note: The orange segments represent new national concentration limits for general areas.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

change mitigation and GHGs emissions reduction towards 2020, making detailed plans on energy conservation, circular economy and low-carbon economy promotion. (People's Government of Zhejiang Province, 2013; Environmental Protection Department of Zhejiang Province, 2013).

Shanghai Clean Air Action Plan (2013–2017) sets the same goal as Zhejiang, to reduce PM emissions by accelerating the implementation of control measures in energy, industry, transportation, construction, agriculture, and residential sectors. Shanghai also issued its plan on industrial energy saving and comprehensive utilization, setting a mix of goals on industrial energy efficiency, total industrial energy use, energy consumption of per 10,000 industrial added value growth, etc. *Shanghai's Twelfth Five-Year-Plan on Energy Conservation and Climate Change* sets goals such as zero growth rate of fossil fuels and 40%–45% reduction of CO_2 emissions per unit GDP in 2020, compared to 2005 (People's Government of Shanghai, 2012) (Environmental Protection Bureau of Shanghai, 2013).

It can be concluded that the three areas of YRD are becoming serious about air pollution and climate change, especially in recent years. The problem is that there are still very little recognition of the co-benefits between air pollution reduction and climate change mitigation within the local government. One example is that these two interrelated issues are respectively addressed in different governmental division, i.e. the Development and Reform Commission is in charge of GHGs reduction while the Environmental Protection Department is responsible for air pollution control. There is a lack of efficient coordination and collaboration between the two government divisions. The good news is that the three areas now are becoming aware of the significance of collaboration in terms of environmental issues. The YRD air pollution prevention coordination mechanism, which was officially launched in January 2014, has gained strong support from the central government and aroused national attention, even though it still lack sufficient detailed co-control measures of GHGs and air pollutants.

3. Methodology

3.1. GAINS model

The Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model is an integrated assessment model developed by scientists from the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. It provides a consistent framework for the analysis of co-benefits reduction strategies from air pollution and greenhouse gas sources. GAINS estimates emissions, mitigation potentials and costs for six air pollutants (SO_2, NO_X, PM, NH_3, VOC) and for the six greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) included in the Kyoto protocol (Amann et al., 2008a). GAINS model was launched in 2006 as an extension to the former Regional Air pollution Information and Simulation (RAINS) model which is used to assess cost-effective response strategies for combating air pollution. GAINS has been used for many macro policy analyses and negotiations in a global scale, and now it serves the whole world in different versions, i.e. GAINS-Europe, GAINS-China, GAINS-South Asia and GAINS for Annex I countries of the UNFCCC Convention, distinguished through modification of the GAINS model regarding the local conditions (IIASA, 2012).

There are a considerable number of studies using GAINS model for the analysis both in Europe and in Asia. Amann et al. (2011) described the detailed methodology of GAINS model and presented a policy analysis exploring the likely future development of emissions and their impacts on air quality in Europe, with a cost-effectiveness assessment. Rafaj et al. (2012) simulated the impacts of GHGs on traditional air pollutants worldwide and for regions of EU, China, India and the US through GAINS, up to 2050. Amann et al. (2008b) estimated the air pollutants and GHGs emissions and their impacts in baseline and alternative policy scenarios to find the most cost-effective measures to address the two issues in China. Kanada et al. (2013) investigated the differences of SO_2 emissions, SO_2 reduction potential, and the cost-effectiveness of reduction policies by using GAINS-China model in five mega-cities in China. Liu et al. (2013) conducted a case study in Beijing using GAINS-City model, which includes some adjustments of the original GAINS model, with policy packages designed and implemented in policy scenarios. GAINS model is a reliable and efficient tool for co-benefits assessment, yet studies focusing on industry sector in a certain region in China are still very rare, hence the study is very necessary to fill this gap.

3.2. Emissions calculation

The emissions of different air pollutants and GHGs are calculated by the following equation by GAINS model, based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied (Amann et al., 2008a):

$$E_{i,p} = \sum_k \sum_m A_{i,k} ef_{i,k,m,p} x_{i,k,m,p} \quad (1)$$

Where i, k, m, p represents region, activity type, abatement measure, pollutant, respectively; $E_{i,p}$ denotes emissions of pollutant p (for SO_2, NO_X, VOC, NH_3, $PM_{2.5}$, CO_2, CH_4, N_2O, etc.) in region i; $A_{i,k}$ denotes activity level of type k (e.g., coal consumption in power plants) in region i; $ef_{i,k,m,p}$ denotes emission factor of pollutant p for activity k in region i after application of control measure m; $x_{i,k,m,p}$ denotes share of total activity of type k in region i to which a control measure m for pollutant p is applied.

GAINS estimates future emissions according to Eq. (1) by varying the activity levels along exogenous projections of anthropogenic driving forces and by adjusting the implementation rates of emission control measures, which includes behavioral changes, structural measures and technical measures.

3.3. Scenario description

The “Baseline11_TS_1s” scenario (Amann et al., 2008) in GAINS-China model is adopted in the analysis. This baseline projection was developed by the Chinese Energy Research Institute (ERI), the collaborative partner of GAINS development team in China, reflecting current Chinese expectations on (i) population projections of the National Population Development Strategy, (ii) the official Chinese industrial process forecasts, (iii) the 1997–2010 Land Plan Program of the Ministry of Land and Resource (2004), (iv) the national government's development targets for renewable energy sources under the 11th Five Year Plan, and (v) the IPAC-AIM/Local energy model.

The baseline scenario extrapolates business-as-usual (BAU) assuming that existing policies on energy and environment will be continued and implemented. Technology progress keeps at a moderate level. International trading will increase and China's economy will be integrated further into the global economy. Therefore, China could rely on international markets and energy imports to meet part of its energy supply needs.

In terms of macroeconomic parameters, the baseline scenario projects an increase of total GDP (in constant 2000 USDs) by a factor of 10 between 2000 and 2030 (i.e., by 8% per year), while total population would increase by 15 percent. This implies a growth in per-capita GDP by a factor of 5.5 from 2005 to 2030 if measured in Market Exchange rates, or by a factor of three in terms of Purchasing Power Parity.

As for energy consumption presumption, the total primary energy consumption is estimated to increase by a factor of 3.2 between 2005 and 2030 under BAU conditions, indicating a clear decoupling between economic growth and energy consumption as a consequence of the ongoing structural transformation of China's economy. Consumption of coal is projected to grow by 80%, mainly for fuel power generation. Oil demand is expected to grow by 160 percent, and renewable energy by a factor of four.

In this paper, GHGs and air pollutants emissions from the industry sector (including power generation sector) of YRD is studied, with the scenario year setting every five year intervals from 2005 to 2030. It's still worth noting that although the scenario is set by authoritative researchers and based on major national policies in China, it still has many uncertainties that can be inconsistent with the real situation. The paper also provides explanation and discussion to the potential uncertainties of the model and its results in the following sections.

4. Results analysis

In this section, the macroeconomic growth and energy consumption amount of YRD from 2005 to 2030 are projected by GAINS-China model; the air pollution emissions, GHGs emissions and health impacts are simulated and analyzed, and the uncertainties related to the results are also discussed.

4.1. Macro-economic development and energy consumption

Based on the population and GDP of Shanghai in 2005, the growth trend of macro economy and population of the three areas of YRD is shown in Fig. 6. Due to the stringent national total population control policy, the population of YRD grows in a marginal rate annually. The ratios of the population increase in Jiangsu, Zhejiang and Shanghai are 11.9%, 15.1% and 11.3% respectively from 2005 to 2030. The total GDP of each area grows at the certain rate (i.e. 8% annually) presumed in baseline scenario, reaching approximately 6 times that of 2005 by the end of 2030. Compared to the real statistics during 2005–2013 in YRD, it can be found that this prediction of the population and GDP trend is highly relevant to the actual data of Jiangsu and Zhejiang (with the deviations no more than ±5%), whereas not exactly reflects the truth of Shanghai, whose population and GDP grow in a rate much higher than predicted (for example, the predicted Shanghai's population in 2010 is 17.81 million, which is 22.7% lower than the real data, i.e. 23.03 million). It may due to the fact that Shanghai is one of China's largest cities and it has been attracting people and capital in a speed beyond its plan over the past decade.

The total energy consumption amount of Jiangsu, Zhejiang and Shanghai will be 2.36, 2.61 and 1.81 times that of 2005 (Fig. 7) respectively in 2030. Energy consumed by the industry sector will still hold the biggest share in the whole, but its proportion will decrease year by year, from 67.6% (Jiangsu), 72.5% (Zhejiang) and 58.5% (Shanghai) in 2005 to 57.2%, 64.4% and 62.1% in 2030. It reflects YRD's diminishing dependence of the industrial economy, and the gradual transformation of the overall economic structure. Comparing to the real statistics of YRD in the period of 2005–2013, the prediction of total energy consumption shows that Jiangsu and Zhejiang's growing trends well coincide with the historic statistics released by local authorities, while Shanghai's result considerably underestimates the energy consumption, which may also result from the model's undervaluation of the denseness and expansion of this metropolis, especially the excessive growth rate of population.

4.2. Air pollutants emissions from the industry sector of YRD

A considerable amount of air pollutants are produced from the industry sector. Fig. 8 illustrates the emissions of different air

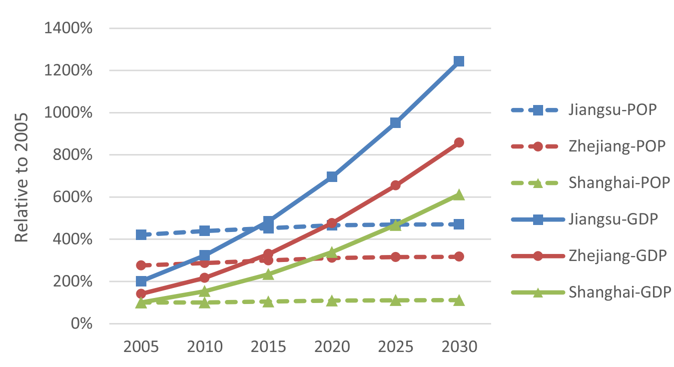

Fig. 6. Economic development and population growth of YRD, 2005–2030.

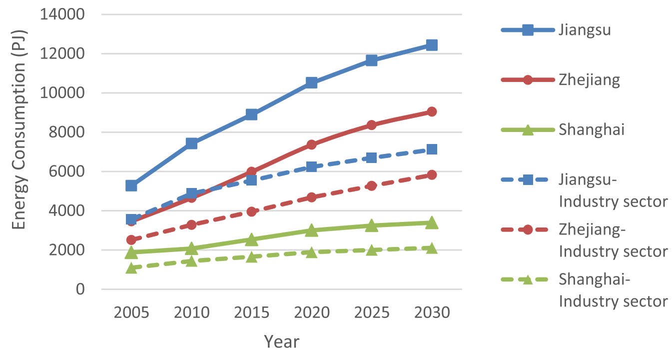

Fig. 7. Total energy consumption and energy consumption of the industry sector of YRD, 2005–2030.

pollutants considered in this part, i.e. SO_2, NO_X and $PM_{2.5}$, three air pollutants which are most concerned currently in China. This result seems quite reasonable if compared to other studies which estimate YRD's air pollutants inventory at a certain historic year (Huang et al., 2011; Fu et al., 2013).

SO_2 control policies, as aforementioned, have been implemented from a relatively early time, so SO_2 emissions would be well under-control in the future. The result shows that SO_2 emissions increase slightly (i.e. 6.5%) for Zhejiang, total emissions of Jiangsu and Shanghai would both decrease, with Shanghai drops a little bit (i.e. 9.6%) and Jiangsu decreases more than one-third of the total amount of 2005, by 2030. In contrast, the SO_2 emissions statistics from the environmental protection bureaus of the three areas during 2005–2013 all show steady decline year by year, with the emission amounts lower than this simulation result.

In terms of NO_X emissions from the industry sector, since the baseline scenario has not taken strict NO_X control measures into consideration, the three areas all show steady growing trends. By 2030, the growth rate of Jiangsu, Zhejiang and Shanghai is 46.6%, 74.0% and 51.0% respectively on the basis of 2005. As China has not taken account of tackling NOx problem until the 12th Five-Year Plan, the NOx emission data of most provinces is unavailable before 2010. Due to the new NOx control policy, the industry sector especially the power generating sector has installed more denitrification facilities, hence the NOx emissions was decreased during 2011–2013, claimed by local environmental protection bureaus of YRD.

As for $PM_{2.5}$ emissions, Jiangsu and Shanghai have similar trends, which show a steady decline after the total emissions reaching the highest point in 2010. Compared to the level of 2010, the $PM_{2.5}$ emissions of Shanghai get 20.2% lower in 2030 while the decrease rate of Jiangsu is 8.8%. In contrary to the other two areas, Zhejiang shows an obvious rising trend, with a 10.7% increase from 2010 to 2030. Usually, in terms of particulate matter, only the emissions of industrial soot and dust were reported in China. It is just in the last few years (i.e. after 2012) that China began to officially monitor $PM_{2.5}$ concentrations, so there's considerable data gap of $PM_{2.5}$ as it was not a mandatory requirement for the local governments to release.

The different status of pollutants emissions among the three areas could attribute to several factors. First of all, the total air pollutants emissions amount is in line with the energy consumption amount, which is mainly driven by economic scale (Wang et al., 2011), hence Jiangsu emits the most air pollutants, followed sequentially by Zhejiang and Shanghai. Secondly, there's good differences of the industrial structure among the three areas. Jiangsu holds more heavy industries such as steel, cement and chemical industry, Zhejiang's industrial economy is relatively more labor-intensive, while Shanghai relies more on its tertiary industry. Thirdly, the enforcement of pollution control policies is varied. For example, Jiangsu banned new power plants construction aside from the 11th Five-Year Plan schedule while Zhejiang did not make

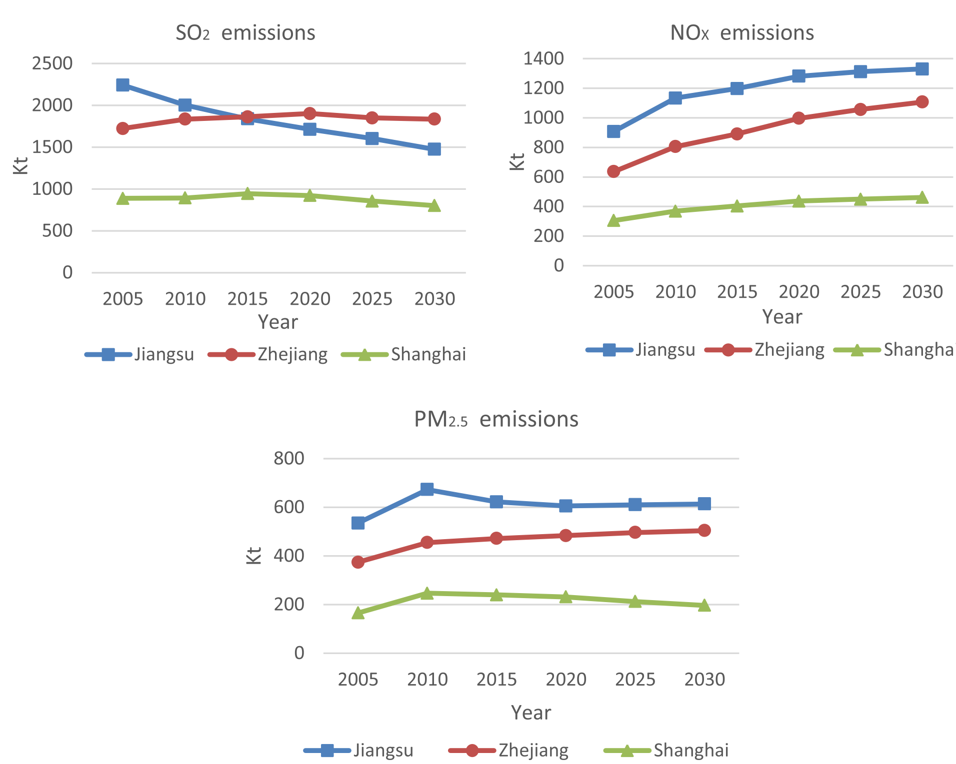

Fig. 8. Air pollutants emissions from the industry sector of YRD, 2005–2030.

such promise. Jiangsu required that 60% of the industrial boilers must install desulphurization facilities, and this goal for Zhejiang was 50%. Furthermore, Jiangsu achieved 3% higher SO_2 reduction target than Zhejiang during 2005–2010.

4.3. GHGs emissions from the industry sector of YRD

Fig. 9 depicts the tendency of GHGs emissions generated by the industry sector of YRD, both from the combustion of fossil fuels and from the industrial process. The total CO_2 emissions are dominant in all GHGs emissions while the N_2O and CH_4 emissions are almost negligible in quantity. While CO_2 is mostly produced in industrial activities, N_2O and CH_4 are, to a large extent, mainly caused by agricultural activities, municipal solid waste disposal. The trends of N_2O emissions of the three areas are quite alike, reaching almost the same amount in 2030, mainly emitted from power generating and chemical processing industries. Shanghai's CH_4 emissions are surprisingly higher than the other two, which mainly result from mining processes, production of oil and gas, as well as waste water from food and paper manufacturing industries.

CO_2 emissions are closely correlated to fossil fuels consumption. The amount of CO_2 emissions increases steadily from 2005 to 2030, with the growth rate ranging from 61.1% (Jiangsu), 89.7% (Shanghai) to 92.2% (Zhejiang). All GHG emissions amount, which could be calculated through the global warming potential (GWP) index of different non-CO_2 GHGs and then converted to CO_2 equivalent, would climb to 696.92, 572.38 and 262.22 Mt CO_2e in 2030 for Jiangsu, Zhejiang and Shanghai respectively, 1.76 times of 2005 level in total. And the all GHGs emissions show a coinciding growing trend with CO_2 emissions, with the growth rate almost the same (±1%) from 2005 to 2030. In general, the eminent increase of GHGs emissions reflects steady growth of total energy consumption and local economy in YRD, and it will undoubtedly raise further concern of problems brought about by local climate change.

This simulation result made by GAINS is in good accordance with several other carbon emissions inventory researches on YRD (Hua et al., 2012; Wang et al., 2013; Li et al., 2010). They either show that the GHGs emissions in YRD in the past years have been increasing at a fast rate, or indicate that they would rise to a new height in the coming decades, if no further measures are taken. The level of GHG emissions could be affected by energy consumption amount, energy structure and industrial structure. As Fig. 4 shows, Jiangsu ranks the first among three areas, no matter in total energy consumption amount or the proportion of industry sector's energy consumption in the whole. And Jiangsu also has the highest proportion of coal in the primary energy structure (70% in 2012), while this ratio in Zhejiang and Shanghai is 58% and 47% respectively. And as aforementioned, Jiangsu has a larger base of carbon-intensive industries than the other two areas, yet it enacted stricter and clearer policies on the phase-out of backward production facilities, and this helps to explain why Jiangsu has the largest reduction ratio in the simulation result.

4.4. Environmental and public health impacts

Years of life lost (YOLL) is an important indicator in GAINS model to assess the health impacts caused by particulate matter concentration. YOLL is affected by both total population and PM concentration of a certain region. Fig. 10 illustrates the $PM_{2.5}$ concentration and YOLL trends of YRD from 2005 to 2030.

The $PM_{2.5}$ concentrations of Jiangsu and Shanghai reach the peak at 2010, and then gradually decline to only 3.6% and 5.7% more than that of 2005, in 2030. As for Zhejiang, the concentration of $PM_{2.5}$ keeps stable from 2010 to 2030, with the highest point (80.94 μg/m^3) appearing in 2020, and is notably lower than Jiangsu and Shanghai, in whole. The population above the age of 30 years old in all three areas increases steadily, and the amount of people affected by PM grows correspondingly, although not proportionally.

The ensemble average years of life lost alters when either the population or the PM concentration changes, showing a complex correlation with the two parameters. It is still under study about the relationship between $PM_{2.5}$ concentration and its impact on human health. The same $PM_{2.5}$ concentration would cause different damages according to the population density (Apte et al., 2012), so even

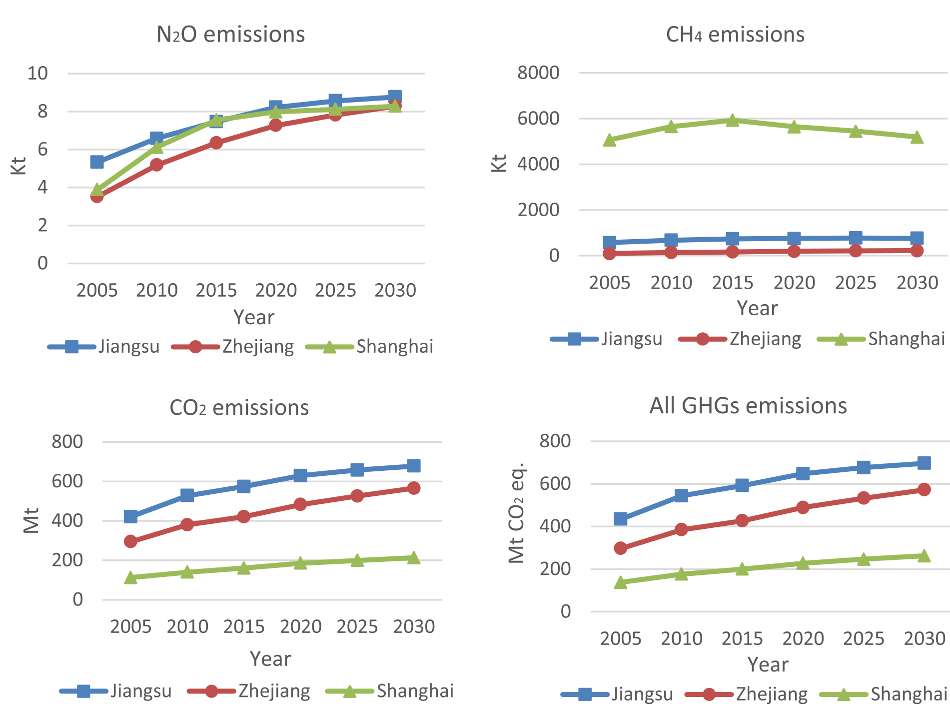

Fig. 9. GHGs emissions from the industry sector of YRD, 2005–2030.

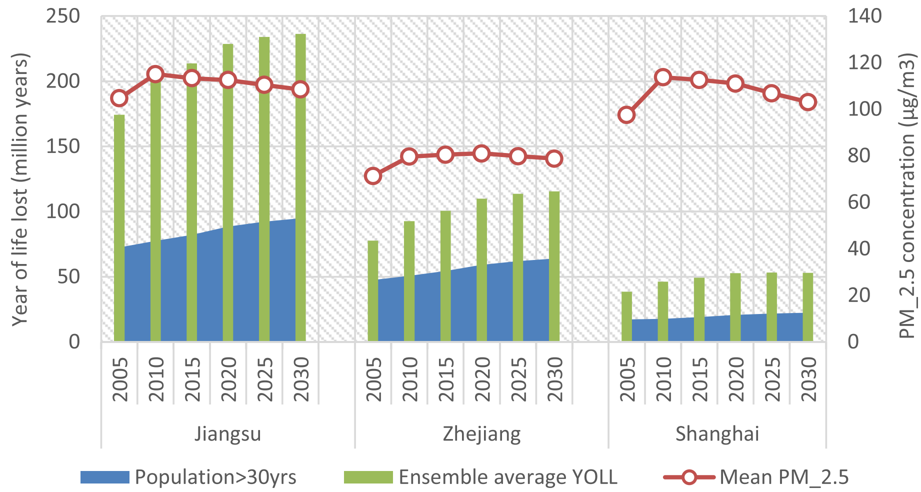

Fig. 10. Years of life lost related to PM in YRD, 2005–2030.

if the $PM_{2.5}$ concentrations would be controlled at a stable level, a growing population still means a growing number of life lost.

4.5. Uncertainty analysis

Several assumptions are made before undertaking the assessment by using GAINS-China model. Therefore, it is essential to discuss the uncertainties and make this study more decent in the process of adopting the model and forming the results.

Firstly, some parameters in the scenario may not be predicted accurately in GAINS. For example, the growth rate of the macro economy is set as 8% each year during 2000–2030. Although in the past decade China has achieved an average annual GDP growth of more than 8%, it is known that China's GDP growth is 7.4%–7.7% in 2012–2014 and may get even lower in the future. Even though YRD's economic growth is higher than the nation's average, it will by no means continuously maintain such a high speed up to 2030. The results may be overestimated in the future when YRD's annual economic growth rate could not reach 8% any longer, thus the total energy consumption would also be less than estimated and therefore it is expected that there would be somewhat less GHGs and air pollutants emissions when the economy slows down.

Secondly, there are great possibilities of policy changes in the future. China is now making stricter regulations on both energy and environmental issues. A series of renewable energy policies and air pollution prevention policies are released in the 12th Five-Year Plan, with targets more ambitious than ever before. And the industry adjustment policies aimed at eliminating low-end manufacturing industries and promoting high-tech industries, would also help to reduce emissions. YRD as a developed zone, would be in a leading role of this transformation. Since the scenario of the study has not taken these newly updated policies into consideration, the estimation gets somewhat pessimistic. If taking account of these emerging measures and more ahead, the emissions are expected to decrease to some extent, depending on the effectiveness of implementing these policies.

Thirdly, the emissions should be considered from a broader perspective. It is known that a significant proportion of China's energy consumption is driven by international demand (Minx et al., 2011). Since YRD is China's largest export base, a large amount of goods are produced to meet foreign consumers' needs, but the emissions from fuel combustion and production process directly damage the local environment. Similarly, part of YRD's consumption can cause the pollution and carbon emissions elsewhere. Additionally, just like rich counties relocate their energy-intense industries to poorer countries (Wagner, 2010), with the environmental policy getting stricter and labor force getting more expensive in YRD, many industries especially manufacturing industries may relocate to the western or middle areas of China. This may reduce the emissions in YRD, but still would not reduce the nation or the planet's total emission amounts. While the air pollution's damage is local, the greenhouse effect is always global.

In order to arrive at reasonable results and conclusions, all of these uncertainties in the application of GAINS need to be considered carefully and necessary improvements need to be taken in the future's study as well.

5. Conclusions and policy implications

GAINS-China model is employed in this study to evaluate the air pollution reduction and climate change mitigation achievements in the industry sector under the current policy of the three areas in YRD, from 2005 to 2030. The macro economy development and energy use status quo of both China and YRD are depicted, the history and current situation of air pollution and GHGs emissions is presented, and detailed national and local policies on both issues are reviewed.

The total population would grow in a marginal rate while the economy of YRD would keep booming in the next two decades, reaching approximately 6 times higher that of 2005 by 2030. The total energy consumption amount of Jiangsu, Zhejiang and Shanghai in 2030 would be 2.36, 2.61 and 1.81 times bigger that of 2005 respectively, with the industry sector still holding the biggest share of the whole, but its proportion would decrease year by year, reflecting the transformation of the overall economic structure of YRD.

SO_2 emissions would be well under-control by 2030, with slight increase for Zhejiang, a little drop for Shanghai and more than one-third decrease for Jiangsu. The NO_X emissions of the three areas all show steady growing trends, with the growth rate ranging from 46.6% to 74.0%. The $PM_{2.5}$ emissions of Jiangsu and Shanghai have similar trends, which show a steady decline after reaching the highest level in 2010, while Zhejiang shows a stable rising trend from 2005 to 2030. And the ensemble average years of life lost has a complex correlation with the total population and the $PM_{2.5}$ concentration trends.

CO_2 emissions are still in predominant position among all the GHGs emissions. In comparison, the N_2O and CH_4 emissions would be much less produced by industry sector. The amounts of CO_2 emissions could increase steadily from 2005 to 2030, with the growth rate ranging from 61.1% (Jiangsu), 89.7% (Shanghai) to 92.2%

(Zhejiang). All GHGs emissions amount would be 1.76 times that of 2005, and it shows a coinciding growing trend with CO_2 emissions, with the growth rate almost the same (±1%) from 2005 to 2030.

Differences in emission situations among three areas may due to some aspects, such as economy scale, industrial composition, energy structure, enforcement rate of policy, etc. Lastly, the uncertainties within GAINS-China model and the results of it are discussed. These uncertainties may come from the inaccurate prediction of scenario parameters and expected policy changes in the future. What's more, the emissions should be considered in a broader view, not just from a regional perspective.

Based on the results analysis part, several policy implications are highlighted. First, YRD should foster more capital and technology intensive industries and restrict the scale of energy-intensive industries. To do that, there would be industry relocation from YRD to less developed areas, and it needs to be carefully considered when it comes to pollutants emissions issue. Secondly, the primary energy structure needs to be improved. The majority of the emissions are resulting from the combustion of fossil fuels, especially coal. YRD should cut down on its high dependence on coal and develop renewable energy more. Thirdly, local governments should consider and take more co-benefits concepts and measures into policy-making and implementing process. Addressing air pollution control and GHGs reduction simultaneously could be both efficient and economical for enhancing the local environmental sustainability. Lastly, three government authorities of YRD should strengthen their cooperation and collaboration on GHGs reduction and air pollution control.

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