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ORIGINAL PAPER

Low-carbon development in the least developed region: a case study of Guangyuan, Sichuan province, southwest China

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Abstract The Wenchuan earthquake in 2008 has resulted in 50% of Guangyuan city facing recovery from different extents of damages. The massive reconstruction provides a good opportunity for Guangyuan city to response to the National Council's call for tackling climate change by developing a harmonised and low-carbon economy. However, there are many arguments about the definition of 'low carbon' and the framework that low-carbon development should follow. Low-carbon development in an economically least developed region such as Guangyuan would provide evidence and contribute to the discussion. The paper employs CO_2 emissions as an environmental indicator in scenario analysis to investigate Guangyuan's future carbon performance in following the national call of reducing 40% of carbon intensity by 2020 and an alternative low-carbon development path. The results have demonstrated that a 'win–win' solution can be reached—keeping rapid economic growth while reducing CO_2 emissions, however, only by addressing the 'correct' determining factors. Technology improvements and production structure changes have been identified as the key determining factors to affect both carbon intensity and CO_2 emissions in the future. The two factors are also interdependent. Governmental policies should give appropriate guideline to address both factors but with strong emphasis on production structure decarbonisation in order to avoid the mistake of 'polluting first and deal with the pollution later' during the emission-intensive industrialisation processes that many western countries and China's coastal regions have followed.

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1 Introduction

Guangyuan city, 300 km northeast of Chengdu, the capital of Sichuan province, was one of the epicentres of an 8.1-magnitude quake and aftershocks in the Wenchuan earthquake in May 2008. The earthquake resulted in the city suffering economic losses of around 127 billion Yuan. The earthquake has resulted of more than 90% of the local houses and the power, telecommunication and water supply infrastructures damaged or destroyed (Li 2010).

Just after the earthquake, the surviving rural households received clear instructions from Guangyuan city government to help them rebuilding their houses. The precise mandate guides the villagers to cut down energy consumption by reconstructing buildings to be designed as less carbon-intensive structures. The city also encouraged massive deployment of solar heating systems to meet the sanitary needs of these villagers. 'Black tiles, walls painted white, sloping roofs on both sides, and wooden doors and windows became the new standard for village homes. This was just one part of our low carbon reconstruction and redevelopment plan', said Aiwu Zhao, the vice-mayor of Guangyuan city. He continues that [Guangyuan is] 'faced with an urgent need for reconstruction and rapid economic development, it has become necessary for us to seize the opportunities and bring in the concept of low carbon development during the initial phase of reconstruction' (quoted after Li 2010).

But Guangyuan is a very 'least developed' region in China, in which Gross Domestic Production (GDP) per capita is only one-third of the Chinese average. The urbanisation rate is only 31% in 2007 versus over 45% as the Chinese average. Agriculture and primary mining and processing (e.g. coking) are dominating industry in Guangyuan's economy.

What is low-carbon development for Guangyuan? How can the region maximise the low-carbon aspect of rapid economic development? What should be the low-carbon development pathway for such least developed regions? The reality is that the local authority in Guangyuan has no existing model to follow as almost all discussions on low-carbon city development have been focussing on wealthy countries or regions. In fact, the 'low-carbon development' is a term without an internationally agreed definition (Mulugetta and Urban 2010).

Therefore, it is no surprise that Guangyuan city council choose to closely follow Chinese national policy on tackling climate change by reducing 40–45% of carbon intensity relative to 2005 level by 2020. The Vice-mayor proposed that technology improvements will make great contributions to low-carbon development in Guangyuan, with a focus on lowering carbon intensity. However, deployments of low-carbon technologies are usually associated with large-scale expansion of production. During China's 12th Five-Year Plan period (2010–2015), Guangyuan will phase out backward capacity in key industries such as cement, ferroalloys, coke and coal mining, which will contribute to energy conservation in future. For example, 'Guangyuan plans to construct a 120 megawatt coal slime power plant with integrated resource utilisation and close down all small scale thermal plants [as they are highly energy inefficient]' (quoted after Li 2010). Coal slime is a by-product resulting from the coal-washing process.

The paper employs CO_2 emissions as an environmental indicator in scenario analysis to investigate Guangyuan's future carbon intensity performance and CO_2 emissions if it follows the national call of reducing 40% of carbon intensity by 2020. An analysis based on such an exercise can be a case study to contribute to discussion on low-carbon development for the least developed regions or countries. The scenario includes an analysis of population growth, per capita income growth, urbanisation and lifestyles changes, as well as economic structural changes, technical change and changes in resource efficiency. The methodology applied in this paper is environmental-extended input–output analysis.

2 Scenario analysis based on input–output analysis

Scenario analysis has become very popular amongst researchers providing an indispensable tool for analysing large-scale interactions between social, economic and environmental systems with long-term horizons (Hubacek et al. 2007). They provide a coherent framework of analysis that can show the development and interaction between the relevant systems and guide discussion on the points of interest (Clark and Munn 1986; Toth et al. 1989; Prieler et al. 1998).

In order to compare different development paths about a society, a framework for evaluation is needed. Input–output tables extended by sustainability indicators provide such a framework (Duchin 1998). The emphasis of input–output analysis is on the structure, interrelationship and state of ecological-economic systems during a certain interval of time, usually a year. The fundamental purpose of the input–output model is to analyse the interdependence of economic sectors. Its extensions include extensions to cover social institutions (e.g. Stone 1970) and to cover the environment (see e.g. Leontief 1970; Victor 1972; Duchin and Lange 1994). Input–output analysis has often been criticised on the grounds that the basic input–output relations are represented by fixed coefficients, given a certain period of time. The assumption behind this is that the physical structure does not automatically respond to changes in prices. Input–output analysis assumes fixed proportion (Leontief-type) production functions, which also means that input functions are linear. This is a limitation for policy analysis since the effects of pricing and regulation policy on final demand have to be assumed. On the other hand, input–output analysis does allow the researcher to deal with discrete and explicit changes in structures (Duchin 1998, p. 80). These changes in structure are derived from scenario developed around each question to be explored. Structural changes include the technology used in different sectors, the share of the different sectors in total, changes in the composition and extent of the different final demand sectors and the availability and quality of different environmental resources. Technical literature and expert knowledge are important sources to provide information on current and potential future production processes, population and other social trends and the environment.

2.1 The Leontief input–output model

The following two sections will concerns many mathematical symbols, formulas and equations. Hereby, for clarity, matrices are indicated by bold, upright capital letters (e.g. $\mathbf{X}$); vectors by bold, upright lower case letters (e.g. $\mathbf{x}$); and scalars by italicised lower case letters (e.g. x). Vectors are columns by definition, so that row vectors are obtained by transposition, indicated by a prime (e.g. $\mathbf{x}'$). A diagonal matrix with the elements of vector $\mathbf{x}$ on its main diagonal and all other entries equal to zero is indicated by a circumflex (e.g. $\hat{\mathbf{x}}$).

The mathematical structure of an input–output system consists of n linear equations in n unknowns, as shown in Eq. 1. The equation depicts that the value of total production is equal to the intermediate deliveries plus final demand for each sector.

$$x_i = z_{i1} + z_{i2} + \cdots + z_{\text{in}} + y_i, \quad i = 1, 2, \ldots, n \tag{1}$$

n the number of economic sectors of an economy, x_i the total output of sector i, y_i the total final demand for sector i's product, z_{in} the intermediate delivery from ith sector to the nth sector.

A fundamental assumption in input–output analysis concerns the interindustry flows from i to j (Miller and Blair 1985), represented as z_{ij}. By dividing z_{ij} by x_j (the total output of jth sector), one can obtain the ratio of input to output—z_{ij}/x_j, denoted as a_{ij}, which reflects the production efficiency with present technology. It is the so-called technical coefficient or direct requirement coefficient that depicts that the requirement from economic sector i to produce one monetary unit of product in economic sector j.

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{2}$$

The fundamental assumption is that a_{ij} represents a fixed relationship between a sector's output and its inputs. Thus, there is an explicit definition of a linear relationship between input and output and there are no economies of scale, rather the Leontief model represents constant returns to scale. Thus, doubling inputs will double outputs; reducing inputs by half will reduce outputs by half. In essence, the coefficients represent the trade from economic sector i to economic sector j. By accepting the notion of technical coefficients, Eq. 1 can be rewritten, replacing each z_{ij} by $a_{ij}x_j$, as showed in Eq. 3

$$\begin{aligned} x_1 &= a_{11}x_1 + a_{12}x_2 + \cdots + a_{1j}x_j + \cdots + a_{1n}x_n + y_1 \\ x_2 &= a_{21}x_1 + a_{22}x_2 + \cdots + a_{2j}x_j + \cdots + a_{2n}x_n + y_2 \\ &\vdots \\ x_i &= a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n + y_i \\ &\vdots \\ x_n &= a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nj}x_j + \cdots + a_{nn}x_n + y_n \end{aligned} \tag{3}$$

In matrix notion (Eq. 4), $\mathbf{A}$ represents the $n \times n$ matrix of technical coefficients (a_{ij}) and $\mathbf{x}$ and $\mathbf{y}$ are the corresponding $n \times 1$ vectors:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \tag{4}$$

Equation 5 comes from rearranging the above Eq. 4:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{5}$$

where the term $(\mathbf{I} - \mathbf{A})^{-1}$ is usually written as $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ which is the so-called Leontief inverse matrix. Matrix $\mathbf{L}$ accounts for the total accumulative effects including both direct and indirect effects on sectoral output by the changes in final demand. In other words, in order that every sector delivers one unit of final demand, every sector has to produce not only its own final demand, but also the direct and indirect requirements needed for its own and the other final demand. The direct requirements in monetary terms means the gross revenues received by producers for final purchases of goods and services by consumers, government and exports; and the indirect requirements are the expenditures on factors of production to input-supply sectors triggered by the direct requirements.

Changes in matrix $\mathbf{L}$ also reflects technical change in the economy, which are changes in the input–output relations of economic sectors.

2.2 Input–output model applications to environmental analysis

Input–output analysis has been applied not only in economic and financial accounting, but has also been extended to account for environmental pollution and abatement associated with interindustry activities. These studies have been conducted since the second half of 1960s. Since then, many scholars have been devoted to extending input–output analysis for research into environmental problems. The input–output analyses have been diversified to many aspects and applied to various economic-environmental related studies. We follow the tradition developed by Leontief (1970) who focused on the flows from the economy to the environment.

Leontief introduced pollution coefficients to relate pollution to the activity of each industry. This basic idea can be extended to account for all types of pollution or resource consumption coefficients and is here applied to carbon emission.

In order to link an environmental indicator, for example the CO_2 emissions, here denoted as **cf**, to economic sectors, the vector representing changes in output ($\Delta\mathbf{x}$) is pre-multiplied by a diagonalised emission coefficients matrix ($\hat{\mathbf{c}}$). The CO_2 emission coefficient vector (c_j) is calculated by dividing total carbon emissions in each sector (cf_j) by total sectoral output (x_j).

$$c_j = \frac{cf_j}{x_j} \quad (6)$$

The CO_2 emission coefficient vector (c_j) represents CO_2 emissions in tons per 10,000 Yuan of output of sector j (see also Wiedmann et al. 2006).

2.3 Scenario settings

In order to make the projections for the total CO_2 emissions in Guangyuan for the year 2020, we determine five main factors and apply widely accepted scenarios for these major driving forces (see Garbaccio et al. 1999; Hubacek and Sun 2001, 2005; Wu et al. 2005; Hubacek et al. 2009).

2.3.1 Economic growth and the consequent per capita income growth

Since 1978, China's GDP has expanded at an average annual rate of 9.7%. In recent years, the growth has achieved double digits. However, the GDP growth in Guangyuan is relatively slower than the national average. According to data from the Guangyuan Statistics Yearbook 2008 (Guangyuan Statistics Bureau 2009), GDP in Guangyuan has increased at 7.8% averaged annually over 1978–2007. The Guangyuan Development and Reform Commission has established a 12% GDP increase per year till 2010, and an annual increase of 10% over its 12th Five-Year Plan (2011–2015) (Guangyuan Development and Reform Commission 2009a, b).

2.3.2 Population dynamics and urbanisation

For China's national population in 2020, we adopt the projection from the Population Group of the International Institute for Applied System Analysis (IIASA) in Austria, which is 1.43 billion in 2020 (Cao 2000). The figure has also been adopted in our previous study (Hubacek et al. 2009). Guangyuan's population was about 3.1 million in 2007, and the natural population growth rate has been around 1% per year since 2000. Furthermore, Guangyuan's urbanisation rate was only 31% in 2007 (Guangyuan Statistics Bureau 2009) and will catch up to the national average of 50% by 2020 according to Guangyuan's development plan (Guangyuan Development and Reform Commission 2009a, b). In order to predict Guangyuan's population in 2020, we use 1% growth rate, and therefore, the figure will achieve 3.5 million by 2020.

2.3.3 Changing consumption patterns

We employ the projected China's consumption pattern in 2020 from our previous study (Hubacek et al. 2009). For the case of Guangyuan, for 2007, household consumption patterns are distinguished between urban and rural households and are taken from the derived Guangyuan input–output table for 2007 (see Sect. 2.4 for details of the construction of the Guangyuan 2007 input–output table). We adopt the income elasticities of demand and per capita income estimations to project consumption pattern changes in 2007 for Guangyuan (Hubacek and Sun 1999, 2001; Hubacek et al. 2009).

2.3.4 Technical and structural change

We followed the same techniques as Hubacek et al. (2009). We adopt the RAS technique to estimate the Leontief technical coefficients matrix (**A** matrix) for 2020, $\mathbf{A}_{2020}$. The RAS method is a widely used method to update an input–output table over a certain time period or to adjust a national table in order to derive a regional table. The basic method is outlined in Miller and Blair (1985). In this paper, we denote the base year matrix by $\mathbf{A}_{2007} = [a_{ij}]$, then each coefficient a_{ij}, is subject to two intertemporal effects: the substitution effect that is measured by the extent to which the output of the *i*th sector has been replaced by other sectoral outputs' intermediate production; the fabrication effect that is measured by the extent to which the ratio of intermediate to total inputs has changed in the *j*th sector. As a result of these two effects, the technical coefficient matrix in 2020 can be computed as $\mathbf{A}_{2020} = \hat{r}\,\mathbf{A}_{2007}\,\hat{s}$. The information of the two diagonal matrices, $\hat{r}$ and $\hat{s}$, can be obtained from estimations of the total output in 2020, $\mathbf{x}_{2020}$, final demand in 2020, $\mathbf{y}_{2020}$ and assumptions about the ratio of value added by primary inputs to total inputs. The estimations of $\mathbf{x}_{2020}$ and $\mathbf{y}_{2020}$ are based on the changes of historical trend of economic production and local experts' judgements on Guangyuan's future economy.

2.3.5 Carbon intensity

In this paper, we project that Guangyuan will follow the national call for '40–45% of carbon intensity reduction by 2020 relative to 2005 level' (quoted after Qiu 2009). We establish a 40% of carbon intensity reduction target by 2020 for Guangyuan, given the fact that Guangyuan is a pre-industrialised region with out-dated production technologies. Then, we estimate the total CO_2 emissions and per capita carbon emissions with projections of Guangyuan's 2020 economy.

2.4 Data

2.4.1 Guangyuan input–output table

We use environmental input–output modelling to assess Guangyuan's carbon performance. The core dataset is an input–output table. China regularly publishes national and provincial input–output tables every 5 years. However, city-level tables rarely exist. Many studies in the literature use the production technology matrix (the **A** matrix) from other sources to establish studies at a local level. For example, the option remains to either use national average or Sichuan provincial production technology matrix as a proxy. However, Guangyuan is an agricultural and industrial material-intensity economy, which is very different from the Sichuan provincial or national economy. In other words, the A matrix from either the Sichuan or national input–output table will not represent Guangyuan's production structure in an appropriate way without adjustment.

Therefore, we need to produce a Guanyuan city input–output table. We firstly interviewed key officials in Guangyuan Development and Reform Commission, Guangyuan Agriculture Bureau, to obtain necessary production and consumption information for Guangyuan. This procedure is important to learn about the dominant economic sectors and key production and export commodities in Guangyuan. Secondly, we obtained national accounts, GDP composition, industrial outputs and consumption data from Guangyuan Statistics Yearbook 2008 (Guangyuan Statistics Bureau 2009) to generate the final demand and value-added section of an input–output table for year 2007. Thirdly, we adopted Sichuan production technology matrix (obtained from Sichuan input–output table 2005 (Sichuan Statistics Bureau 2007) and use the RAS technique to generate a Guangyuan-oriented production technology matrix for 2007.

The Guangyuan input–output table is at the aggregation level of 42 by 42 economic sectors. This is a commodity-by-commodity table based on the assumption of homogeneous sector output. This means that each commodity is produced by only one industry and each industry produces only one product. The 'value-added' categories in the table include capital depreciation, labour compensation, taxes and profits. 'Final use' comprises six categories: rural households, urban households, government consumption, fixed investment, inventory changes and net exports. The negative numbers in the net-flow column reflect a negative trade balance (exports minus imports).

2.4.2 Energy inventory and CO_2 emission data

An energy balance table is essential for CO_2 emission accounting. China conducts a regular energy inventory and publishes annual energy balance tables at both national and provincial level every year. However, this is not always the case when the scale is down to city level. Guangyuan, one of the least developed regions in China, does not possess a completed energy inventory system; in other words, the local statistical authority has never compiled an energy balance table for Guangyuan. In order to guarantee the data quality, we have interviewed key officials from Guangyuan Development and Reform Commission, Guangyuan Statistics Bureau, Guangyuan Electricity Bureau, and Guangyuan Agriculture Bureau to obtain the necessary information and some raw statistics, then we generate an energy balance table for Guangyuan in 2007, which is used in this paper.

Furthermore, we also need industrial final energy consumption data in sectoral detail in order to apply the environmental input–output analysis to assess the carbon emissions. From Guangyuan Statistics Yearbook 2008 (Guangyuan Statistics Bureau 2009), we obtained sectoral industrial final energy consumption data for large and medium size enterprises. Such data for all types of industries do not exist. We were informed by Guangyuan Development and Reform Commission during the interview that the large and medium size enterprises could account for approximately 80% of final energy consumption. In terms of this estimation, we are able to generate the overall industrial final energy consumption in sectoral detail.

CO_2 emissions from combustion of fuels and industrial processes were calculated using the IPCC reference approach (IPCC 2006). The energy and emissions data for both years comprise 38 production sectors and 2 households sectors (urban and rural). The normalisation process between energy data and input–output tables follows our previous work (Peters et al. 2007; Guan et al. 2008, 2009).

3 Results

3.1 Guangyuan carbon performance 2007

Guangyuan's production-related CO_2 emissions in its territory boundary in 2007 was 5.72 million tons of CO_2. Per capita CO_2 emissions was 1.86 tons, which is approximately 1/3 of national average, 1/6 of UK level and 1/10 of US level. Guangyuan carbon intensity is 2.5 tons per 10,000 Yuan in 2007, 10% higher than the national average of 2.3 tons per 10,000 Yuan.

Primary and secondary energy processing industrial sectors are the dominating sources of Guangyuan's direct CO_2 emissions in 2007, which together accounted for over 70% of the total emissions. For example, of the 5.72 million tons of emissions, 67% or 3.8 million tons of emissions were from coal-fired electricity production and coal mining and processing industry[1]; 15% or 0.86 million tons of emissions were from coking and its refining sector. The rest 18% or 1 million tons of CO_2 emissions were shared among non-metallic material processing such as cement production (4% or 250 thousand tons), agriculture (3% or 170 thousand tons), construction (2%, 10 thousand tons) and other sectors.

If we account for both direct and indirect emissions from the perspective of the entire production supply chain, the CO_2 emission discharge in 2007 was primarily driven by the construction and petroleum refinery sectors; 8.8 million tons of CO_2 emissions were discharged throughout the entire production supply chain in order to fulfil the goods and services demand in the construction sector in Guangyuan. In other words, using the consumption emission accounting approach (see Peters 2008), Guangyuan's construction activities are responsible for 8.8 million tons of CO_2 emissions in 2007. The reason that the emissions are even higher than Guangyuan's total territorial emissions (5.72 million tons) is that large amounts of cement, steel and other products were imported from other Chinese regions to fulfil Guangyuan's construction activities. Similarly, the metal processing sector was responsible for 3.95 million tons of CO_2 emissions in 2007.

In contrast, there are 8.73 million tons of CO_2 emissions embedded in Guangyuan coking industry's net exports (exports minus imports). In other words, consumers in other Chinese regions are responsible for 8.73 million tons of CO_2 emissions due to their consumption of Guangyuan's coking products. Likewise, there are 1.14 and 1.06 million tons of CO_2 emissions embedded in Guangyuan's net exports of non-metallic materials (e.g. cement and glass) and wearing apparel products. The calculation is based on an assumption that the production technologies of Guangyuan's exports and imports are the same as those for all Guangyuan's production. This assumption is widely applied when a full multi-regional model is not available (Peters et al. 2007).

[1] The reason to group electricity and coal mining and processing sectors together here is due to the limitation of official statistics in Guangyuan. Almost all large coal mining sites have their own small scale coal-fired electricity plant(s). They produce the electricity for their production and residential needs. Our calculation largely relies on current available statistics that have not been able to separate the two sectors.

3.2 Guangyuan carbon performance in 2020

In this section, we firstly introduce the projected economic conditions for Guangyuan in 2020 according to the projection assumptions set out in Sect. 2.3. Secondly, we calculate Guangyuan's 2020 CO_2 emissions and analyse the main driving forces under the 40% carbon intensity reduction scenario.

3.2.1 Guangyuan economic condition in 2020

In terms of the projection, Guangyuan's GDP growth is planned to be 9.8% annually averaged over 2008–2020. The level of GDP will reach 7.7 billion Yuan by 2020 from 2.3 billion Yuan in 2007 (in constant prices of 2007). The population will grow 13% to 3.5 million by 2020 from 3.1 million in 2007. The urbanisation process will be accelerated to achieve 50% in 2020 from 21% in 2007, which will significantly influence personal consumption patterns and economic final demand distributions. The great disparities of income levels and consumption expenditure patterns between rural and urban households will be further enlarged. As a result, per capita consumption in rural household will increase from 1,773 Yuan in 2007 (Guangyuan Statistics Bureau 2009) to 2,622 Yuan in 2020, while per capita consumption in urban household will reach 11,802 Yuan from 7,572 Yuan (Guangyuan Statistics Bureau 2009) during the same period. Personal consumption patterns will also shift from more agricultural and primary industrial products to more services. For example, the share of agricultural products will decrease from 36% in 2007 to 28% by 2020, while the share of industrial goods and services would slightly increase from 34 and 30% to 37 and 35%, respectively, during the same period.

Furthermore, the consumption patterns in urban households would change significantly. The share of agricultural products will decrease from 18 to 13% and the share of industrial goods and services would increase from 44 and 38% to 46 and 41%, respectively.

3.2.2 Pathway of achieving the '40% carbon intensity' target

Guangyuan has identified a number of possible solutions to achieve the target. However, the main efforts have been invested in energy sector. The implementations include

- Construction of 7 new hydro-power plants. Current total installed capacity of hydro-power plants in Guangyuan is 863,000 kW. The newly installed capacity will be 1.3 million kilowatts to achieve a 2 million kilowatts total capacity by 2012.
- Adopt low calorific value coal for coal-fired power plants. Guangyuan authority plans to achieve a target of 60% low calorific value coal by 2012.
- Investments on geothermal energy and forestry carbon sink project. Guangyuan is rich in geothermal energy and forestry resource. Guangyuan's forest cover rate has reached 907,000 hectares—59% of the total land area, which is 17% higher than the national average.

3.2.3 CO_2 emissions under the '40% carbon intensity' reduction scenario

- If Guangyuan would achieve averagely 40% of carbon intensity reduction relative to the 2005 level by 2020, at the lower end of the 40–45% reduction range announced as the Chinese national target in the Copenhagen Accord, Guangyuan's production-related CO_2 emissions would decrease by 4% to 5.52 million tons due to the continuously rapid economic development. Furthermore, the per capita CO_2 emissions (territory accounting inventory) would reduce by 17% to 1.59 ton per year by 2020 from 1.86 ton per year in 2007.

- If we analyse the source of Guangyuan's direct CO_2 emissions under this scenario, primary energy mining and processing sectors would still be the major driver, which is similar to the 2007 situation. Electricity generation and coal mining will account for 59% (3.1 million tons) and coking sectors will produce 11% (0.6 million tons) of overall CO_2 emissions.
- If we investigate both direct and indirect CO_2 emissions from the perspective of the whole product lifecycles, construction will be responsible for 8.58 million tons of CO_2 emissions, while electricity generation will be responsible for 2.25 million tons of CO_2 emissions. On the other hand, Guangyuan would export 231 million Yuan from its coking sector, and such export will result in 5.24 million tons of CO_2 embedded in the products. Other major net exporting products including non-metallic products, metal products and coal would result in 1.27, 0.56 and 0.63 million tons of CO_2, respectively, discharged in Guangyuan but for consumption in other Chinese regions.

4 Low-carbon development pathway for Guangyuan

It seems that the above exercise has illustrated that, under plausible assumptions, a least developed region, i.e. Guangyuan could achieve a 'win–win' solution of keeping rapid economic growth with a reduced CO_2 emission level by following the national strategy of 40% of carbon intensity reduction. However, the carbon intensity reduction is largely determined by technology improvements and production structure decarbonisation. Further, the two factors are interdependent. For example, low-carbon technologies deployments are usually adopted by carbon-intensive production sectors (e.g. power industry) and associated with large-scale expansion of production practice that would further decarbonise the production structure. The above scenario assumes the carbon intensity will reduce by 40% for all sectors regardless of rebound effects and wider impacts to the regional economy. In reality, technology can rarely achieve an even improvement among all sectors, and such rebound effects may result in emission increase.

Guangyuan is at the stage of pre-industrialisation. Non-carbon-intensive production such as in agriculture and general services are largely contributing to its economy. The industrial productions are usually engaged with primary resources mining and processing, which is associated with very high emissions intensity. In terms of the latest governmental plan, Guangyuan local authority is interested to attract investments via both domestic and foreign channels to build large-scale electrolytic aluminium and cement production base. The newly built energy intensive factories may have the latest technology; hence, the sectoral carbon intensity would significantly drop comparing with the small-scale production Guangyuan currently has. But the price paid of heavily expanding aluminium and cements production is rapid growth of emissions, which repeats the same development path as many western countries as well as the economically advanced coastal regions in China.

The alternative effort to achieve low-carbon development for Guangyuan is to focus on the other determining factor—the production structure. China has a coal-dominated energy consumption structure, which coal accounts for almost 70% of total energy use. Although coal is still the dominated energy source for Guangyuan's economy, the proportion is much less about 62% of total energy use; renewable energy (e.g. hydro power) has a greater share

(17%) compared to the Chinese national average (7%) (National Bureau of Statistics 2008; Guangyuan Statistics Bureau 2009). Further, Guangyuan has great potential to enlarge the development and utilisation of natural gas (lower carbon emission) and renewable energy, particularly hydro power and bio-gas.

Hydro power accounts for about 80% or 2.1 TWh of total electricity generation in Guangyuan while the rest, 20% or 560 GWh, is covered by coal-fired power plants. Of course, the electricity production generated by Guangyuan itself can only fulfil 60% of total consumption in terms of both industrial and household consumption. The gap is filled by importing electricity from other regions, which usually produced by coal-fired plants. The Guangyuan local authority will continue utilising renewable energy and developing lower carbon emission fossil fuel (e.g. natural gas) in order to gradually increase its own supply of electricity. By 2015, Guangyuan plans to complete the construction of 1.5 GW hydro-power plants, 1.1 GW in 'Tingzikou', 600 MW natural gas plants and 5×1 MW bio-gas electricity generators for rural households' consumption (Guangyuan Development and Reform Commission 2009a, b).

Furthermore, Guangyuan aims to take the advantage of low-carbon development to promote the concept of circular flows for its economic growth. Guangyuan traditionally has a good reputation in some high value-added agricultural products—green tea, forestry products and kiwi fruits. However, the planting scale is relative small and based on family units. Guangyuan local authority has invested and encouraged centralised and large-scale planting (Guangyuan Agriculture Bureau 2009), which could potentially benefit local employment and accelerate production structure change towards low-carbon but high value-added industrial development.

If Guangyuan follows the low-carbon development pathway by focusing on the determining factors of energy mix and production structure, the carbon intensity for the entire regional economy will reduce more than 60% of 2007 level, and the per capita CO_2 emissions will reduce to less than one ton per person, half of 2007 level and two-third of the 40% carbon intensity reduction scenario.

There are many ways of achieving the CO_2 intensity target, that the ways for Guangyuan to achieve it should follow general development taking into account co-benefits (air quality, energy security, rural employment and congestion), that the 40% target should be the minimum expected of a sector unless there are exceptional circumstances and there should be no maximum, and that market instruments such as emission trading should be introduced.

Last but not the least, the economically least developed regions or countries have their unique characteristics to maintain economic growth, which can be low-carbon but high value added agriculture and services, and policy makers should try to encourage these aspects so as to leapfrog, but not mimic, the industrialisation and modernisation pattern that developed regions have been through over the past many decades.

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