Resources Policy 43 (2015) 11–18

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

# Production forecast of China's rare earths based on the Generalized Weng model and policy recommendations

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ARTICLE INFO

*Article history:*
Received 3 September 2014
Received in revised form
10 October 2014
Accepted 10 November 2014
Available online 28 November 2014

*Keywords:*
Rare earths
Generalized Weng model
Production forecasting
By mine types
Policy recommendations

ABSTRACT

China is currently the largest producer of rare earths in the world, mining at least 90% of world total production. Because of China's dominant position in global rare earths production and the constant development of rare earths terminal industries, the study of China's rare earth supply trends has gradually been a hot topic of world interest. However, the literature shows that previous research has mainly focused on the estimation of rare earth supply and its influence based on experiential judge of current and premonitory new rare earth production capacity, rather than on quantitative modeling. The results are usually estimations of the productions of near future rather than longer term. Forecasts by mine types are particularly rare. Considering the different applications and demands of different rare earth elements, the Generalized Weng model, a widely used quantitative model in exhaustible resource forecast, is adopted in this study to predict the production of the three major rare earths in China (namely, mixed rare earth, bastnasite and ion-absorbed rare earth) before 2050. The results show that production of mixed rare earth will peak in 2014 at 62,757 t, followed thereafter by an annual decline of 2%; production of bastnasite will peak in 2018 at 32,312 t, preceded by an annual increase of 1.67% and followed by an annual decrease of 4%; production of ion-absorbed rare earth will peak in 2024 at 45,793 t, preceded by an annual increase of 1.72% and followed by an annual decrease of 4%. Based on these findings, Chinese government should enforce environmental and resource exhaustible taxes soon and different domestic regulations for different rare earths according to their different production potential. Countries without resource endowments should make efforts to develop rare earth recycling technologies and seek substitutes for rare earth resources, in addition to keeping good international trading relationships. Countries with some kind of rare earths should start or restart their rare earth mines to gradually reduce dependence on China's supply.

## Introduction

Rare earth elements (REEs) are performing important functions in our everyday life with their wide use in a range of products (McLellan et al., 2013). Meanwhile rare earths (REs) are also indispensable elements in modern industry with the uses in new energy, new materials, energy conservation, environmental protection, aerospace, and electronic information industries because of their unique physical and chemical properties. To protect the environment and ensure sustainable supply, the Chinese government implemented a series of policies to limit production and export. After several initiatives since 2006 to restrict the supply, the United State, the European Union, and Japan challenged China as lawsuit for violating provisions of its membership in the World Trade Organization (Ministry of Commerce People's Republic of China, 2014). It is easy to see from the lawsuit case that rare earth resources have been one of the targets of world competition accompanied by continuous development in rare earths-related industries.

There are currently 110 million tons of REEs proven reserves globally. Half of these reserves are located in China, with Russia accounting for another 17.3% and the United States for 11.8%. Sizeable deposits are also found in Brazil, India, Australia, Canada and Greenland (Wübbeke, 2013). The United States was the leading producer of rare earths from 1940s to mid-1980s, when it provided the majority of REs to the rest of world from the Mountain Pass mine in California which is one of the best minable deposits in the world (Gschneidner, 2011; Morrison and Tang, 2012). With the abundant and low-price REs supplies from China, Mountain Pass was unable to compete. Moreover, given the mine's

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http://dx.doi.org/10.1016/j.resourpol.2014.11.002

increasing ecological costs as a result of a halt in chemical processing in 1998 on the back of a series of wastewater leaks, operations ended in 2002 (Currie, 2012).

China gradually has entered the international market for rare earths since the 1980s, and China's rare earth production has maintained an absolute leading position since 1986. During the 1990s, China's REs production increased sharply (He and Lei, 2013). China's overall rare earth mine production has almost become synonymous with global production since 2004. Obviously, China has become the world's largest producer, user, and exporter of REs in the recent decade with 97% share of global RE production (Massari and Ruberti, 2013).

With the constant development of rare earths terminal industries, the study of China's rare earth supply trends has gradually been a hot topic of world interest. However, literatures show that previous researches have mainly focused on the estimation of rare earth supply and its influence based on experiential judge of current and premonitory new rare earth production capacity, rather than on quantitative modeling. The results are usually estimations of the productions of near future rather than longer term. Forecasts by ore types are particularly rare.

Considering the exhaustible nature of rare earths and different applications and demands of different rare earth elements, the Generalized Weng model, a widely used quantitative model in exhaustible resource forecast, is adopted in this study to predict the production of the three major rare earths in China (namely, mixed rare earth, bastnasite and ion-absorbed rare earth) before 2050 and policy recommendations for different countries have been proposed based on the research results.

## Literature review

### *Prediction of exhaustible resources*

Exhaustible resources and energy are the basis of national economic development. The prediction of exhaustible resources and energy production is of profound significance, in that it not only assists governments to work out long-term resource and energy strategic plans but also helps to maintain sustainable social and economic development. Prediction of exhaustible resource production has its origin in oil sector. By middle of 20th century, methods of predicting field-level production were used in evaluating producing fields (Arps, 1945). In the 1950s and 1960s, curve-fitting techniques were used to forecast production (Hubbert, 1956). After the oil crisis of 1973, elevating resource depletion was to be a topic of vigorous theoretical exploration (Krautkraemer, 1998). And finally, the 1970s and 1980s saw increasing focus on econometric modeling of oil discovery and extraction (Walls, 1992). After that, the three techniques were applied to production prediction of other exhaustible resources and proved to be very effective for this purpose. Nevertheless, Brandt contends that all three techniques have its defect. For example, theoretical exploration and econometric model require the quantification of a large number of relationships and correlations, often in the face of conflicting or nonexistent data (Brandt, 2010). The curve-fitting technique is too dependent on original curves of event where no more flexibility of adjustment exists to variables. However, compared with the other two methods, the curve-fitting technique is the least data needed, particularly in the case of China's REs where the relevant data are especially difficult to get.

Among curve-fitting techniques, many scholars have adopted the Hubbert model (a typical bell curve model, which was first proposed by Hubbert) in production forecasting of energy (Bartlett, 2000; Hubbert, 1956; Zittel, 2007; Höök and Aleklett, 2009; Höök et al., 2010; Lin and Liu, 2010). After the Hubbert model, a variety of Hubbert-like curve-fitting models appeared, two among which are the Gaussian model (Bartlett, 2000; Brandt, 2007) and the Gompertz model (Moore, 1962, 1966). These models share properties of the Hubbert method while relaxing or altering some of its assumptions. Chinese scholars put forward the HCZ model (Feng et al., 2008; Hu et al., 1995) as well as the Generalized Weng model (Chen and Hu, 1996; Lv et al., 2012; Tang et al., 2009; Qiang et al., 1995), based on their studies of the curve-fitting techniques. These two models have mainly been used by Chinese scholars in their later research.

### *Prediction of REEs*

Because of the extensive application of REEs and the important position of China's RE reserves and production, studies on RE production have been increasing. Kingsnorth reported that the RE supply of other countries apart from China will increase significantly during 2011–2015, based on an analysis of the foreign RE companies' production and operation planning, RE research programs in these companies, and Japan's overseas RE investment projects. They also pointed out that the global RE supply will exceed the demand after 2013, and China's share of the supply will decrease (Kingsnorth, 2010b). Kingsnorth predicted that by 2014, China's RE production will reach 160,000–170,000 t (Kingsnorth, 2010a). Chen Zhanheng reported that foreign RE production capacity will exceed 170,000 t after 2015 by evaluating the rare project investment of all continents, and China's RE production will only account for 64% of global supplies if the foreign RE projects proceed as planned and domestic RE production can be maintained at 85,000 t as achieved in 2013. He also reported that foreign RE demand will be at least 80,000 t in 2015, and the lack of foreign supply of REs will reach 18,000–50,000 t if China's export quotas are set between 32,000 t and 35,000 t (Chen, 2011). Zheng Minggui by analyzing the reports of ≪Situation and Policies of China's Rare Earth Industry≫ and ≪Critical Rare Earths≫ and combined with the distribution of globe Rare Earth reserves predicted that China's share of the world's RE supply would be reduced to 77% by 2013 and reduced to 43% by 2017 (Zheng and Chen, 2012). In the case of China's restrictions on RE exports, Castor indicated that the Mountain Pass RE Mine in US may be reopened, and its RE output depends on China's export restrictions, price increase, and the growth of domestic demand and other factors (Castor and Hedrick, 2006). Based on China's Rare Earth Development Plan (2009–2015) and media reports, Wübbeke analyzed China's rare earth export policy and the development trend of China's rare earth terminal industry and indicated that by 2015, there will be no new RE mine projects and predicted that by 2015, China's RE output will be maintained between130,000 t and150,000 t and exports will be less than 35,000 t (Wübbeke, 2013). Hurst explored the history of rare earth elements and China's current monopoly of the industry, including possible repercussions and strategic implications if rare earth elements supply was to be disrupted and mentioned that by the middle of the next decade, China's RE output is expected to reach 160,000 t per year (Hurst, 2010). Based on documentary Research Methods, He and Lei point out that U.S. re-emerging REs industry will lead to a significant impact of RE supply surplus in total on future global and its internal REs demands. Nonetheless, the global including U.S. demand of Heavy REEs will still rely on China's supply (He and Lei, 2013).

### *Research orientations*

By reviewing the previous literature, some research orientations have been found. First, many quantitative models have been used in exhaustible resources forecast for a long time, especially the curve-fitting techniques. However, each method has its own

**Table 1**
Curve-fitting models in exhaustible resource forecasting.

| Model | Production forecasting formula | Variable | Parameters |
|---|---|---|---|
| Hubbert | $Q=\frac{abN_Re^{-bt}}{(1+ae^{-bt})^2}$ | $N_R$ $t$ | $a$ $b$ |
| Gaussian | $Q_t=Q_{max}e^{\left(-(t-T_{peak})^2/2\sigma^2\right)}$ | $Q_{max}$ $T_{peak}\sigma$ | – |
| Gompertz | $Q=N_Ra^{b^t}$ | $N_R$ $t$ | $a$ $b$ |
| HCZ | $Q=aN_Re^{\left(-(a/b)e^{-bt}-bt\right)}$ | $N_R$ $t$ | $a$ $b$ |
| Generalized Weng | $Q_t=at^be^{-(t/c)}$ | $t$ | $a$ $b$ $c$ |

$Q$ denotes the production of REEs at time $t$; $N_R$ is called the ultimate reserves, which are the cumulative production after all recoverable reserves have been produced; $t$ is the year corresponding to the peak; $a$, $b$ and $c$ are simply statistical parameters; $Q_{max}$ is the maximum production (peak production); $T_{peak}$ is the year of peak production; $\sigma$ is the standard deviation of the production curve.

defect with regard to the requirements of data source or data processing for variables, as Table 1 shows in the curve-fitting models. As suggested by the name "rare earths", data concerning the details of rare earth reserve, production or price, happen to be really rare. Models chosen to forecast the production should fit the possibility of data acquisition.

Second, the previous research on RE production forecast mainly focuses on estimating global and Chinese RE production based on the current and premonitory production capacity of RE mines or programs worldwide, while few papers are found to forecast peak production and trends of REs with quantitative models. The results are usually estimations of the productions of near future rather than longer term.

Third, few literatures show production forecast by different ore types of rare earth, though it is particularly important because of the different applications of different rare earth ores with different demands. One of the reasons for the rarity may be the difficulty of obtaining related data. Taking the total REs reserves of China in 2009 as an example, this ultimate reserve value is estimated by Su Bo, the Vice Minister of China's Ministry of Industry, who announced that the UR of China's REs were 18,590,000 t on June 20th, 2012, while the U.S. Geological Survey estimated it on Mineral Commodity Summaries (USGS, 2009) to be 27 million tons. We may anticipate that in models where total reserve is a variable, the difference of these two figures will lead to results of major difference.

To provide more reliable and detailed base for rare earth decision of both short and longer term, quantitative forecasting by different ore types is imperious when suitable techniques are chosen.

## Methodology and data

Rare earths produced in China come principally from the mixed rare earth mines, ion-absorbed rare earth mines and the bastnasite mines. China's rare earth production in the future will remain dependent on the three sources (Wang, 2010). So the productions of these three ores are to be forecasted in this paper. As discussed above, theoretical exploration and econometric model require large number of relationships and correlations relying on sufficient historical data, curve-fitting techniques need the least data. Among the curve-fitting models, the Generalized Weng model is best suited for rare earth production forecasting since only in this model $N_R$ is not needed in calculation. There have been no statistical data showing the reserves of China's three major REs—mixed rare earth, ion-absorbed rare earth and bastnasite.

### *Adaptation of Generalized Weng model*

WENG Wenbo, academician of the Chinese Academy of Sciences, stated in his treatise *A Primer in Prediction Theory* (1984) that all things would experience a natural course of "rise–grow–decline". He believed that the annual output of gas and petroleum can be seen figuratively as a small life cycle within a finite system. On one hand, the output increases in power function along with further exploration and the time variable $t$, but on the other hand it attenuates in negative exponent along with reduction in the amount of remaining resources and the time variable $t$. From such presumption he put forward the Poisson circle model, often known as the Weng model. Weng first advanced the Weng model to forecast oil and gas production (Weng, 1984) and subsequently Chen developed a theoretical derivation of the Weng model by establishing the Generalized Weng model as follows (Chen and Hu, 1996):

$$Q_t=at^be^{-(t/c)}$$

Feng et al. (2010) improved the single cycle of Generalized Weng model by establishing the multicyclic Generalized Weng model and then forecast global natural gas production by using this new improved model. Zhao et al. (2009) proposed a new solution based on a linear iterative trial and error method for solving the Generalized Weng model.

Wang forecast the production of China's natural gas by using the Hubbert model and Generalized Weng model and indicate that the Generalized Weng model is more acceptable than Hubbert model. Compared with the Hubbert model, the shape of Generalized Weng curve is not necessarily symmetrical while it also produces a flatter peak, indicating a longer peak plateau which fit better with the reality of China's oil and gas field exploitation (Zhu et al., 2008; Wang et al., 2011) as Laherrere (2000) mentioned that the actual historical oil and gas production curve is generally asymmetrical.

Feng et al. (2007) used the Hubbert model, HCZ model and Generalized Weng model to predict the peak production of China's oil, assuming the absence of a unified reasonable plan for oil production, and the result forecasting by Generalized Weng model is more accurate. The result indicated that China's oil production peak time will occur in 2017 with a peak production of 185 million tons in that year; while the oil consumption peak will occur in the years after 2034, and the number will be up to 633 million tons.

Tang et al. (2009) researched the peak production of oil in North America, Central and South America, Europe, Middle East, Africa and Asia Pacific areas based on the Generalized Weng model. They point out that the future oil pattern would become increasingly dependent on the Middle East, while Asia-Pacific region would become the most serious imbalance between oil supply and demand.

Feng et al. (2006) summarized the differences between domestic and foreign methods for predicting the peak production of oil. They concluded that foreign scholars develop the methods from a single-cycle model to a multi-cycle model, focusing on the vertical development of models, while in China the methods developed mostly are from the Weng model to a series of predictive models, focusing on horizontal development of models.

From literature review, it may be found that Generalized Weng model has been actively applied in the field of exhaustible energy resource forecast and reasonable results have been achieved. It should be a proper choice to borrow the Generalized Weng model to do the forecasting in this paper.

### *Parameters estimation of a, b, c*

In order to obtain the value of equation parameters $a$, $b$ and $c$, the parameter $b$ should be given first, and then parameters $a$ and $c$ can be obtained through regression. The regression data sets are chosen from different periods through 1988 to 2010 by calculating $\ln(Q/t^b)$ based on the real production data of mixed rare earth, bastnasite and ionic rare earth. The preferable linear relation data set is to be selected as regression data set. The specific process is as follows:

As stated in Table 1, the Generalized Weng model is expressed as follows:

$$Q_t = at^b e^{-(t/c)} \tag{1}$$

where $Q_t$ is resource production at time $t$ and $a$, $b$ and $c$ are simply statistical parameters. To get $Q_t$, the values of $a$, $b$, $c$ have to be assigned first.

To solve the forecasting parameters, Chen (1996) proposed the following linear goal seeking methods by changing Eq. (1) as follows:

$$Q/t^b = ae^{-t/c} \tag{2}$$

By taking logarithms on both sides of Eq. (2), this gives

$$\ln\left(Q/t^b\right) = \ln a + \frac{1}{2.303c}t \tag{3}$$

When

$$A = \ln a \tag{4}$$

$$B = 1/(2.303c) \tag{5}$$

Eq. (3) can be written as

$$\ln\left(Q/t^b\right) = A - Bt \tag{6}$$

According to the data series of actual production of each year $Q$ and corresponding time $t$, we can assign different values to $b$ and use formula (6) to do the regression to obtain $A$ and $B$. And then substitute the values $A$ and $B$ into Eqs. (4) and (5) to get the values of $a$ and $c$.

Substitute the different values $a$, $b$ and $c$ which are obtained from the above methods into Eq. (1), multiple sets of productions can be calculated. The $b$ value which gives the best goodness of fit between real cumulative production and predicted cumulative production is the desired $b$ value.

During the actual operation in this paper, in order to solve Eq. (6), the value of parameter $b$ should be given first, and then the value of $A$ and $B$ can be obtained through Microsoft Excel goal seeking methods. Then the value of $a$ and $c$ can be obtained through Eqs. (4) and (5). Finally, we can forecast $Q$ by substituting $a$, $b$ and $c$ into Eq. (1) as shown in Table 2.

**Table 2**
Generalized Weng model.

| Peak model | Basic equations | Peak production | Peak time |
|---|---|---|---|
| Weng's model | $Q = at^b e^{-t/c}$;<br>$N_R = ac^{b+1}\Gamma(b+1)$ | $Q_{max} = a(bc/2.718)^b$ | $t_{max} = bc$ |

### Data description

#### Data source

According to data availability and satisfaction, the data in this paper start from 1988 and end in 2010. The annual production data of mixed rare earths, bastnasite mine and ionic rare earths are taken from The National Development and Reform Commission, Industry Coordination Department of PRC (The National Development and Reform Commission, 1998–2011).

#### Data test

As stated above, the preferable linear relation data set of real rare earth production is to be selected as regression data set. The data set of mixed rare earth is chosen from 1994 to 2010 with their stationary test (unit root test of Phillips–Perron test) statistic$= -5.6383828 < -4.440739$ (1% level) and significance test Prob$<0.05$, $F=77.18>4.494$ (the critical value). The data set of bastnasite data set is chosen from 2000 to 2010 with their stationary test (unit root test of Phillips–Perron test) statistic$= -4.435312 < -3.632896$ (5% level) and significance test Prob$<0.05$, $F=61.86>4.965$ (the critical value). The data set of ionic rare earth is chosen from 1994 to 2010 with their stationary test (unit root test of Phillips–Perron test) statistic$= -6.428356 < -4.440739$ (1% level) and significance test Prob$<0.05$, $F=14.55>4.494$ (the critical value). The historical data of mixed rare earth, bastnasite mine and ionic rare earths all passed stationary test and significance test. The data can be used to calculate parameters $a$ and $c$ in regression.

#### Data processing

The production curve of bastnasite mine experiences a significant fluctuation in 2006 and 2007. In 2006, the bastnasite mine in Sichuan Province of China was found of illegal and excessive exploitation, so

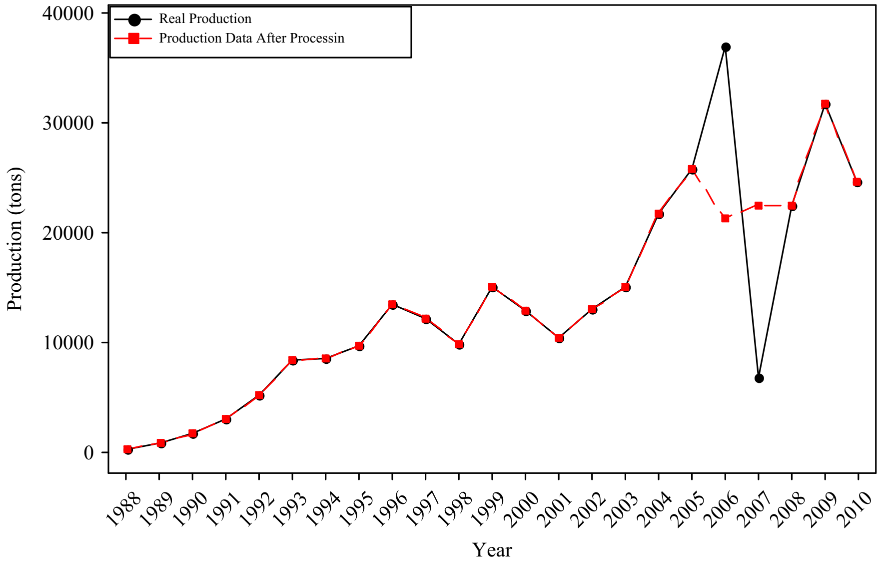

**Fig. 1.** Historical trend of China's bastnaside mine production.
*Data source*: The National Development and Reform Commission (1998–2011).

that the production soared from 25,709 t in 2005 to 37,000 t in 2006. As a sanction, the central government imposed a production limitation on this mining area and the production in 2007 dived to 6800 t. In order to diminish the impact of the dramatic production fluctuation in 2006 and 2007, their figures for those two years were set as missing value, and the linear interpolation method was employed to replace the original figures. The new figures for 2006 and 2007 are 21,301 t and 22,454 t, respectively (Fig. 1).

## Results and discussion

A systematic elaboration on the Generalized Weng model has been presented above. In this section, the Generalized Weng model is employed to predict the production trends and peaks of China's mixed rare earth, bastnasite and ion-absorbed rare earth respectively (Table 3 and Figs. 2–4).

### *Mixed rare earths*

We chose the period of 1994 through 2010 from the data of China's mixed rare earths production which shows the best linear relations. By the linear goal seeking methods, the forecasting parameters were obtained: $a=1234.38$, $b=1.7$, $c=16.13$, and $R^2=0.9997$ for regression segment. When $a$, $b$ and $c$ were substituted into Eq. (1), the future productions of mixed rare earths could be predicted. The forecasts show that China's production of mixed rare earths will peak in 2014 at 62,757 t, followed by a steady decline rate of 2% in the ensuing years (Fig. 2).

### *Bastnasite rare earths*

We chose the period of 2000 through 2010 from the data of China's bastnasite rare earths production which shows the best linear relations. By the linear goal seeking methods, the forecasting parameters were obtained: $a=3.15$, $b=3.8$, $c=8.13$ and $R^2=0.9994$ for regression segment. When $a$, $b$ and $c$ were substituted into Eq. (1), the future productions of bastnasite could be predicted. The forecasts show that China's production of bastnasite will peak in 2018 at 32,312 t, preceded by an annual increase of 1.67% and followed by a steady annual decline rate of 4% in the ensuing years (Fig. 3).

### *Ion-absorbed rare earths*

We chose the period of 1994 through 2010 from the data of China's ion-absorbed rare earths production which shows the best linear relations. By the linear goal seeking methods, the forecasting parameters were obtained: $a=67.88$, $b=2.5$, $c=14.72$ and $R^2=0.9962$ for regression segment. When $a$, $b$ and $c$ were substituted into Eq. (1), the future productions of ion-absorbed rare earths could be predicted. The forecasts show that China's production of ion-absorbed rare earths will peak in 2024 at 45,793 t, preceded by an annual increase of 1.72% and followed by a steady annual decline of 4% in the ensuing years (Fig. 4).

### *Discussion*

First, from the comparison in Figs. 2–4, the predicted results of the three ores have a high degree of agreement with the actual productions from 1988 to 2010. The difference between the predicted and actual production for mixed rare earths, bastnasite and ion-absorbed rare earths averages to 1.4%, 1.1% and 2%, respectively. The forecasts are relatively reliable. The difference of total production between the predicted and the actual of the three types of rare earths may also be obtained which are averaged to mere 1.1% with its peak in 2018 at 138,476 t (Fig. 5).

**Table 3**
Generalized Weng model.

| Year | Mixed RE | Bastnasite | Ion-absorbed RE | Total |
|---|---|---|---|---|
| 1988 | 1160.16 | 2.79 | 63.42 | 1226.37 |
| 1989 | 3542.75 | 34.35 | 335.20 | 3912.31 |
| 1990 | 6633.86 | 141.80 | 863.05 | 7638.72 |
| 1991 | 10,167.93 | 374.12 | 1655.34 | 12,197.39 |
| 1992 | 13,965.29 | 772.37 | 2701.87 | 17,439.53 |
| 1993 | 17,894.87 | 1365.43 | 3982.16 | 23,242.46 |
| 1994 | 21,857.90 | 2168.82 | 5470.00 | 29,496.72 |
| 1995 | 25,778.95 | 3185.29 | 7136.24 | 36,100.48 |
| 1996 | 29,600.22 | 4406.41 | 8950.61 | 42,957.23 |
| 1997 | 33,277.68 | 5814.60 | 10,882.98 | 49,975.26 |
| 1998 | 36,778.25 | 7385.30 | 12,904.21 | 57,067.76 |
| 1999 | 40,077.63 | 9089.10 | 14,986.66 | 64,153.39 |
| 2000 | 43,158.67 | 10,893.64 | 17,104.56 | 71,156.87 |
| 2001 | 46,010.02 | 12,765.30 | 19,234.26 | 78,009.58 |
| 2002 | 48,625.08 | 14,670.59 | 21,354.30 | 84,649.97 |
| 2003 | 51,001.10 | 16,577.27 | 23,445.48 | 91,023.85 |
| 2004 | 53,138.48 | 18,455.22 | 25,490.79 | 97,084.49 |
| 2005 | 55,040.16 | 20,277.06 | 27,475.41 | 102,792.63 |
| 2006 | 56,711.09 | 22,018.59 | 29,386.56 | 108,116.23 |
| 2007 | 58,157.84 | 23,658.98 | 31,213.44 | 113,030.25 |
| 2008 | 59,388.24 | 25,180.92 | 32,947.06 | 117,516.22 |
| 2009 | 60,411.09 | 26,570.56 | 34,580.16 | 121,561.80 |
| 2010 | 61,235.86 | 27,817.40 | 36,107.03 | 125,160.29 |
| 2011 | 61,872.55 | 28,914.10 | 37,523.39 | 128,310.05 |
| 2012 | 62,331.47 | 29,856.25 | 38,826.29 | 131,014.01 |
| 2013 | 62,623.08 | 30,642.08 | 40,013.92 | 133,279.08 |
| 2014 | 62,757.92 | 31,272.17 | 41,085.54 | 135,115.64 |
| 2015 | 62,746.46 | 31,749.18 | 42,041.34 | 136,536.98 |
| 2016 | 62,599.03 | 32,077.51 | 42,882.32 | 137,558.86 |
| 2017 | 62,325.76 | 32,263.04 | 43,610.22 | 138,199.02 |
| 2018 | 61,936.51 | 32,312.84 | 44,227.38 | 138,476.74 |
| 2019 | 61,440.85 | 32,234.94 | 44,736.69 | 138,412.48 |
| 2020 | 60,848.01 | 32,038.06 | 45,141.46 | 138,027.53 |
| 2021 | 60,166.85 | 31,731.41 | 45,445.39 | 137,343.65 |
| 2022 | 59,405.85 | 31,324.51 | 45,652.50 | 136,382.86 |
| 2023 | 58,573.10 | 30,827.02 | 45,767.01 | 135,167.12 |
| 2024 | 57,676.28 | 30,248.57 | 45,793.36 | 133,718.21 |
| 2025 | 56,722.70 | 29,598.67 | 45,736.09 | 132,057.45 |
| 2026 | 55,719.22 | 28,886.59 | 45,599.85 | 130,205.65 |
| 2027 | 54,672.33 | 28,121.27 | 45,389.32 | 128,182.93 |
| 2028 | 53,588.13 | 27,311.27 | 45,109.21 | 126,008.61 |
| 2029 | 52,472.31 | 26,464.69 | 44,764.18 | 123,701.19 |
| 2030 | 51,330.23 | 25,589.15 | 44,358.87 | 121,278.25 |
| 2031 | 50,166.85 | 24,691.77 | 43,897.81 | 118,756.42 |
| 2032 | 48,986.79 | 23,779.12 | 43,385.47 | 116,151.38 |
| 2033 | 47,794.33 | 22,857.27 | 42,826.19 | 113,477.79 |
| 2034 | 46,593.45 | 21,931.72 | 42,224.19 | 110,749.36 |
| 2035 | 45,387.79 | 21,007.47 | 41,583.56 | 107,978.82 |
| 2036 | 44,180.71 | 20,089.00 | 40,908.23 | 105,177.94 |
| 2037 | 42,975.29 | 19,180.31 | 40,201.97 | 102,357.56 |
| 2038 | 41,774.33 | 18,284.89 | 39,468.41 | 99,527.63 |
| 2039 | 40,580.40 | 17,405.83 | 38,711.00 | 96,697.22 |
| 2040 | 39,395.81 | 16,545.75 | 37,933.03 | 93,874.59 |
| 2041 | 38,222.65 | 15,706.91 | 37,137.63 | 91,067.19 |
| 2042 | 37,062.82 | 14,891.18 | 36,327.73 | 88,281.73 |
| 2043 | 35,917.98 | 14,100.08 | 35,506.14 | 85,524.20 |
| 2044 | 34,789.64 | 13,334.84 | 34,675.48 | 82,799.95 |
| 2045 | 33,679.12 | 12,596.38 | 33,838.19 | 80,113.69 |
| 2046 | 32,587.57 | 11,885.39 | 32,996.59 | 77,469.55 |
| 2047 | 31,516.00 | 11,202.29 | 32,152.81 | 74,871.10 |
| 2048 | 30,465.27 | 10,547.31 | 31,308.86 | 72,321.45 |
| 2049 | 29,436.12 | 9920.49 | 30,466.59 | 69,823.20 |
| 2050 | 28,429.17 | 9321.69 | 29,627.69 | 67,378.55 |

Second, the predicted results are quite close to the estimates of previous research. As stated in the review part, some research has been done and the productions of rare earths in the near future have been forecast by Kingsnorth (2010b), Chen (2011), Wübbeke (2013), Hurst (2010), He and Lei (2013) etc. The similar results proved the reliability of the prediction in this paper in some way

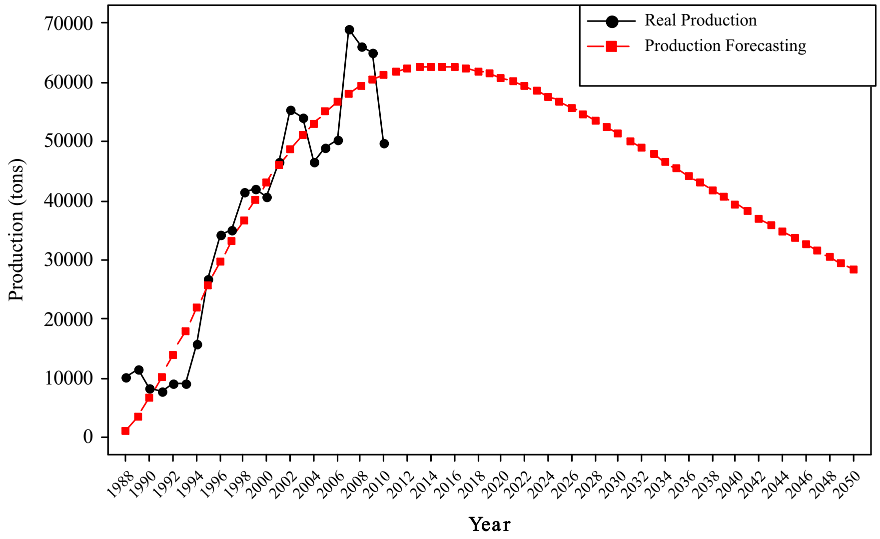

**Fig. 2.** China's mixed rare earths production forecasting.

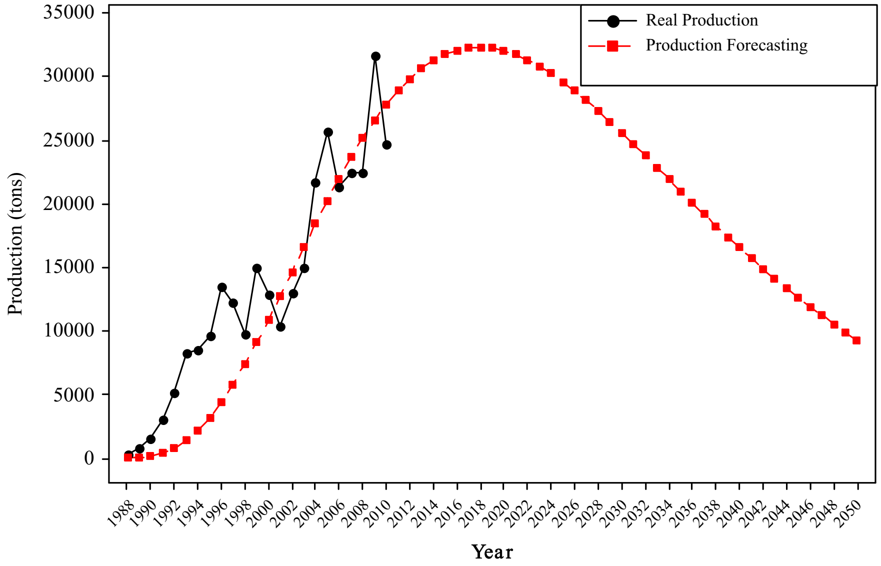

**Fig. 3.** China's bastnasite production forecasting.

since most of the previous results are based on practical experience or national or companies' plans though only for short term.

## Conclusions and recommendations

### *Conclusions*

Based on the prediction and analysis of results in the Discussion, some conclusions are drawn.

(1) By 2020, China's supply of mixed rare earths and bastnasite will begin to decline steadily and China's dominant position will end. To be specific, the production of mixed rare earths in China will peak in 2014 at 62,757 t, followed by an annual decline rate of 2%; that of bastnasite will peak in 2018 at 32,312 t, followed by an annual decline rate of 4%.
(2) By 2024, China's supply of ion-absorbed rare earths will see a trend of continued growth at an annual rate of 1.72%, after which it will decrease on a yearly basis of 4%.
(3) By 2050, China's production of mixed rare earths, bastnasite and ion-absorbed rare earths will account for 45%, 28% and 64% of its peak value respectively, which indicates that ion-absorbed rare earths production will experience the smallest scale of decrease by 2050.

### *Policy recommendations*

With the continuous development of rare earth terminal industries in and out of China, rare earths have been a target of world competition. Rare earths are distributed unequally in the world with 50% of the reserves located in China and about 30% in Russian and the United States. As for heavy rare earths (mainly refers to ion-absorbing type rare earths ore and xenotime), it is even incredibly endowed mostly in Longnan of China, Lehat of Malaysia and Strange Lake of Canada (Chen, 2011). Countries with or without rare earths should value the unrenewable resources and make suitable policies to ensure the supply for demand.

### *China*

Chinese government should enforce environmental and resource exhaustible taxes soon and different domestic regulations

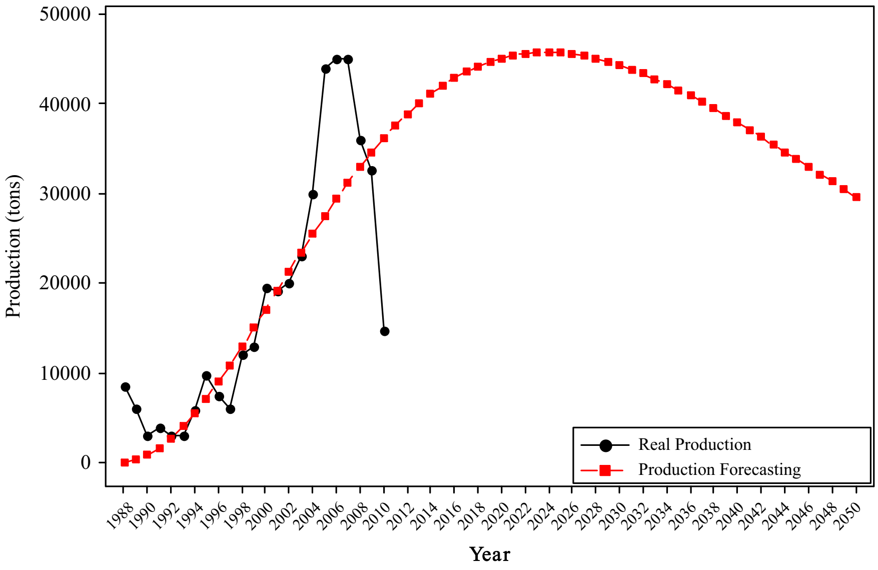

**Fig. 4.** China's ion-absorbed rare earths production forecasting.

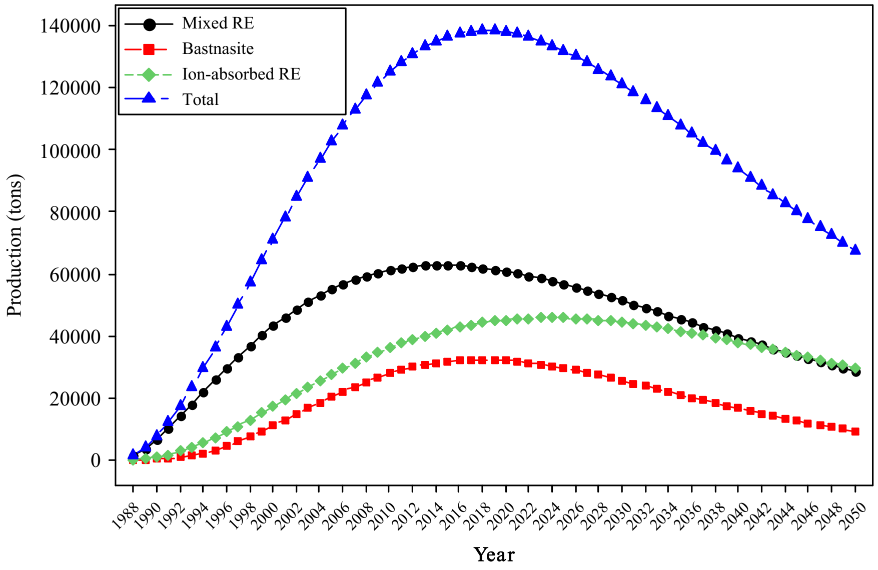

**Fig. 5.** Three types of rare earths production forecasting.

for different rare earths according to the different production potential of different ores.

The monopolistic position of China in production and export of rare earths relies mostly on their low price in which the costs of environmental protection and resource remuneration have not been properly included. In fact, the rare earths for export are ridiculously cheaper than their own value, which results to that increases in export volume do not bring the same increases in export value (Ye and Wu, 2014). Low price coupled with overexploitation gives rise to a series of problems. He et al. (2014) mentioned that overproduction will accelerate the exhaustion of RE resources, and may well create a black market in RE products. So the system of environmental and resource taxes should be established and put into action soon.

As shown in the results, the three main rare earths in China will reach their peaks within only 10 years. However, more of other countries are endowed with light rare earths (including mixed rare earths, bastnasite) which implies that other countries will not depend on China's supply so keenly in the next few years as predicted by many previous research. It is a wise strategy for Chinese government to pay more attention to the research of substitute technologies of light rare earths and build longer industry chains to get more profit from rare earth resources. For heavy rare earths (mainly refers to ion-absorbed rare earth), China should first integrate the mining rights and mining companies to get the highest efficiency of exploitation and the best effect of environmental protection.

### *Other countries*

Countries with RE resources need to start or restart their RE mines to gradually reduce dependence on China, such as the U.S., Russia, Australia, India, etc.(Table 4).

Given the pattern of supply of REs in the world (China accounting for 97% of the world's supply of REs), a world-wide RE supply and demand gap will appear after the peak. Thus, countries with rare earths should consider starting or restarting their RE mines and relieving the world's RE supply pressure.

**Table 4**
Rare earths supply situation oversea.
*Sources*: Ye and Wu (2014).

| Major supply mines | Total reserves (in 10,000 t) | Starting year of supply | Planned annual production (t) | Elements available |
|---|---|---|---|---|
| Mountain Pass, U.S. | 180 | From 2012 | 40,000 | La, Ce, Pr, Nd, Sm |
| Bear Lodge, U.S. | 40 | 2015 | 10,000 | La, Ce, Pr, Nd, Sm |
| Bokan Mountain, U.S. | 30 | 2014–2016 | NA | La, Ce, Nd, Sm, Gd, Y, Dy |
| Tomtor, Russia | 15,000 | After 2023 (an estimate) | NA | Y, Nd oxides, Sc and Tb |
| Mt. Weld, Australia | 120 | 2012 | 11,000 | Mainly light rare earths |
| Nolans, Australia | 85 | 2012 | 20,000 | Rare-earth oxides |
| Dubbo, Australia | 65 | 2013 | 2580 | Light rare earths and yttrium |
| Total | 15,520 | – | 93,580 | – |

*Notes:* The rare earth elements can be grouped as light rare earth elements—La, Ce, Pr, Nd, and middle and heavy rare earth elements—Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y. Sc is of dispersed elements, and Pm does not exist in nature (Xu, 1995).

Countries without rare earth resources need to get prepared to face with the risk of price rising especially for ion-absorbed rare earths. It is welcome for these countries to find ways to recycle resources and consider alternative technologies in addition to keeping close political and economic ties with China and other countries with REs.

## Acknowledgments

We would like to thank the reviewers of this journal for helpful comments and suggestions. Thanks also goes to Ms Wenhui Chen for her help in data testing. This research is supported by the National Natural Science Foundation of China under Grant no. 71241027 and 71203203 and the support from the Development and Research Center of China Geological Survey under Grant no. 12120113093200.

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