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Uranium resources in China's phosphate rocks – identifying low-hanging fruits

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Abstract. China is rapidly increasing its nuclear power fleet of light water reactors and will as a result need more and more uranium fuel. For now, Beijing is following a strategy known as 'three third rule' when it comes to the nation's uranium supply: 1/3 of the uranium comes from domestic mining, 1/3 is obtained through direct international trade, and 1/3 is provided by Chinese companies mining abroad. To date, China has approximately 5% of world's identified primary uranium resources (U.S.$ <130/kg uranium) as defined by the International Atomic Energy Agency but may operate 50% of the global nuclear power fleet by 2050. Domestic unconventional uranium resources that could decrease China's dependence on foreign uranium suppliers are mostly associated with lignite, black shales and phosphate rocks. Extracting uranium from phosphate rock during fertilizer production is a well-known process that is at the edge of being monetarily profitable. Besides, this practice reduces uranium loads on agricultural soils from fertilizers drastically. In this work, we discuss potential unconventional uranium resources that could be extracted in China during phosphate rock processing. We conclude that China, the largest phosphate rock producing country in the world, could theoretically recover some 700 t unconventional uranium annually or roughly 40% of the domestically mined uranium in 2017. Most deposits show low (<30 ppm) to very low (<10 ppm) uranium concentration though that would not favor extraction. Deposits with higher (>100 ppm) uranium content exist in China, and are identified here. Uranium recovered from these deposits, and uranium recovered from imported phosphate rocks processed in China may support domestic uranium mining and as a result energy security of the Middle Kingdom.

1. Introduction

Future development of nuclear power is regarded a necessity in China [1–3] to address increasing air pollution resulting from excessively relying on burning fossil fuels for energy production. As of March 31, 2018, China had 38 commercial nuclear power plants (excluding Taiwan) with an installed capacity of 36,933.16 MWe (rated installed capacity) [4]. In 2017, China's cumulative power generation was 62,758.20 billion kWh. The cumulative power generation of commercial nuclear power units was 247.469 billion kWh, accounting for 3.94% of the national cumulative power generation, an increase of 17.55% relative to 2016. Compared with coal-fired power generation, nuclear power generation is equivalent to reducing the burning of standard coal by 76.467 million tons, reducing emissions of carbon dioxide by 2003.46 million tons, reducing emissions of sulfur dioxide by 650 million tons, and reducing NO_x emissions by 565,900 tons [4]. Although the share of nuclear power is still relatively small compared to primary energy production with coal (Figure 1) [5], China is rapidly increasing nuclear energy production [6]. Figure 2 shows three scenarios (low-, middle-, and high scenario) for the projected uranium demand in China according to Chen et al. [7] until the year 2030.

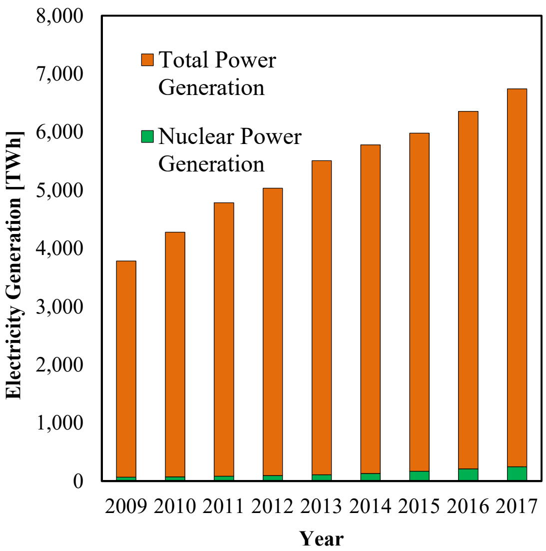

Figure 1. China's annual electricity generation and nuclear power generation in 2009-2017 [4].

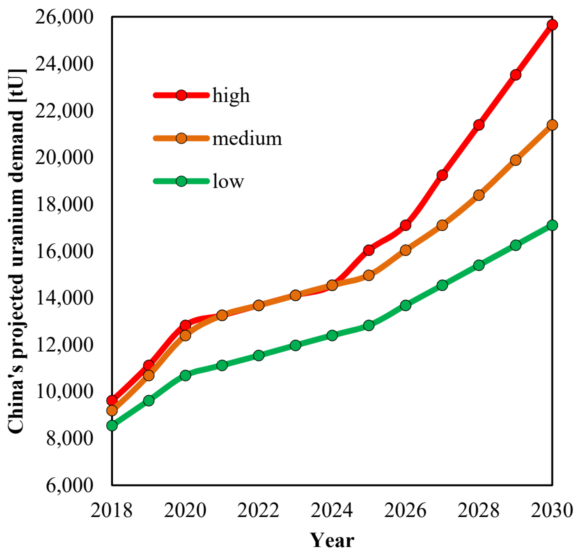

Figure 2. China's uranium demand to 2030 according to Chen et al. [7].

Other studies (e.g. [8]) that estimate different future demands are available. All studies are projecting an increased (two- or threefold) uranium demand for China until 2030. Despite these projections it should be noted that China is actively working on several fast reactor concepts to enable a closed fuel cycle that may change nuclear fuel demands in the very far future [9]. Within this century uranium will, however, be the primary fuel source for nuclear power plants in China.

2. Conventional uranium resources and uranium supply in China

China is currently following a strategy known as 'three third rule' when it comes to the nations uranium supply: 1/3 of the uranium is supplied from domestic mining, 1/3 is supplied from direct international trades and 1/3 is provided from Chinese companies mining abroad [10,11]. China has to date approximately 5% of worlds identified uranium resources (U.S.$ <130/kg uranium) as defined by the International Atomic Energy Agency (IAEA) [12]. Figure 3 provides a brief overview of the world's identified uranium resources in 2015.

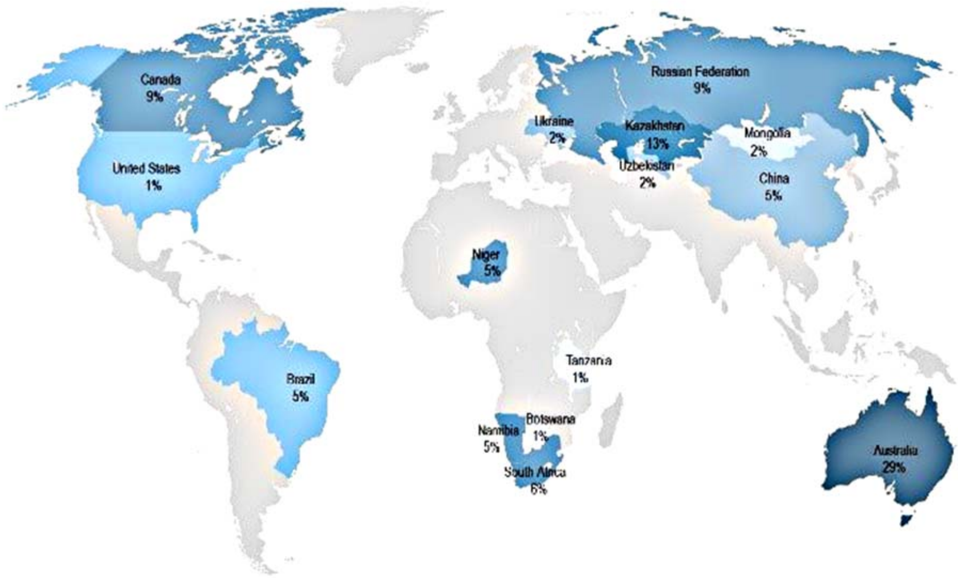

Figure 3. Global identified (U.S.$ <130/kg uranium) uranium resources by country [12].

China has great potential to increase its domestic uranium resources since large areas have only been screened and not explored in depth yet [10]. Although the United States and France, for instance, are heavily relying on imports of natural uranium for their nuclear power fleets an increased future shortage of uranium, resulting in increased market dependence and a potential threat to energy security has been identified by a number of researchers for China [13–26].

3. Unconventional uranium resources in China's phosphate rocks

Black shales have been identified as a relevant unconventional uranium resource in China by Qi et al. [27]. In addition, uranium from domestic and foreign resources may be extracted from China's phosphate rocks during phosphate fertilizer production. Phosphate rock, pre-concentrated phosphate ore, is pre-dominantly used for mineral phosphate fertilizer production. China is to date the largest phosphate rock processing country in the world [28]. It is well known that phosphate rocks can contain considerable amounts of associated uranium and rare earth elements (REEs) [29–32] that can be extracted during wet phosphoric acid fertilizer production if this is desired [33]. Techniques to extract uranium from phosphate rocks during fertilizer production, such as solvent extraction, have been reviewed by Beltrami et al. [34], Singh et al. [35] and Zhong [36], are available and were used in the United States and to a smaller extend elsewhere on industrial scale in the 1980s [37]. Besides, a full scale extraction plant already operated successfully in Taiwan for more than six years starting in May 1981 [38]. Figure 4 schematically shows how uranium recovery during phosphoric acid production from phosphate rock with sulfuric acid was conducted on industrial scale in the past.

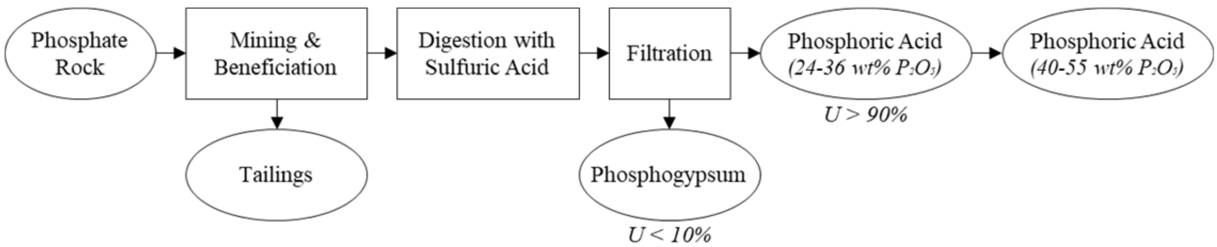

Figure 4. Phosphoric acid production with uranium recovery by the wet-acid process.

It is worth noting that uranium recovery units can be integrated without much effort in operating phosphoric acid plants. Increased environmental awareness, energy independence and potentially rising uranium prices lead to renewed interest in the recovery of uranium from phosphoric acid. The Nuclear Materials Authority in Egypt and Urtek LLC [39] for instance are operating pilot plants for the recovery of uranium from phosphoric acid. In addition, innovative technologies that promise a significant increase in uranium recovery with dramatically decreased accumulation of unwanted phosphogypsum stacks are being developed in parallel [40].

With the largest phosphate rock mining industry worldwide in place, China may have great potential to extract considerable amounts of uranium during phosphate fertilizer production and add this uranium to the amount of domestically mined resources. In this way dependencies on international markets that may affect the Middle Kingdom's energy security in the future could be reduced. In addition, phosphate fertilizers with greatly reduced uranium content would be produced. Hu et al. [41] presented this vision of cleaner fertilizers and increased energy security for China's future. Ulrich et al. [42] later estimated that some 710 t natural uranium could have been extracted from wet phosphoric acid during phosphate fertilizer production in China in 2010. This amount would be sufficient to cover the annual uranium needs of two large (1000 MWe) light water nuclear power plants that each need approximately 305 t natural uranium per year (given 5% enrichment and no uranium losses from natural uranium to nuclear reactor fuel manufacturing).

Hu et al. [41] and Ulrich et al. [42] used average uranium concentrations of 21-31 mg/kg as reported by Van Kauwenbergh [43], and annual phosphate rock production data as reported by the United States Geological Survey (USGS) to estimate the quantity of unconventional uranium that could have theoretically been recovered during phosphate rock processing in China. For first technical and economic feasibility studies it is useful to identify the uranium deposits with the highest uranium concentrations. Qin [44] for instance identified four uranium-bearing phosphate deposits in Gansu, Guizhou, Ningxia and Xinjiang that show uranium concentrations of 100-300 mg/kg and thus raise expectations that uranium from China's phosphate rocks may have the chance to be extracted economically. The data [43,45,46] in Table 1 is a first attempt to summarize the uranium contents from different phosphate rock deposits in China and to identify the most promising deposits for uranium extraction. The World Nuclear Association (WNA) differentiates between (1) very high-grade uranium ores (>200,000 ppm), (2) high-grade uranium ores (>20,000 ppm), (3) low-grade uranium ores (>1,000 ppm) and (4) very low-grade uranium ores (>100 ppm) [47]. If a cut-off grade of 100 ppm is applied, six deposits: Tongrenba (Guizhou, 200-280 ppm), Hanzhong (Shaanxi, 100-300 ppm), Emei (Sichuan, 100-230 ppm), Leibo (Sichuan, 170-480 ppm), Huidong (Sichuan, 100-230 ppm) and Pujiang (Zhejiang, 150-300 ppm) become promising deposits that should be further investigated.

In addition, China may choose to recover uranium from phosphate rock imports. Although, China is the largest phosphate rock producer in the world at the moment the vast majority of phosphate rocks are found in Northern Africa and the Middle East, and here particularly in Morocco (roughly ¾ of all phosphate rock reserves) [28]. Phosphate rock from Morocco contains uranium at concentrations above 100 ppm and is already imported into China in small quantities today (62,500 t in 2016 [48]). It is not unusual that phosphate rock processing plants rely exclusively on imported rather than domestic phosphate rock. Material flows are for instance available for a phosphate fertilizer plant in the Philippines that processed imported phosphate rock from Algeria, Egypt, Jordan, Morocco and Peru the last years [49]. In 2017, China mined some 140 million t phosphate rock [50]. If this phosphate rock would have been supplied by Morocco with a uranium content of 100 ppm and this uranium would have been extracted with a recovery rate of 0.855 (90% transfers to the phosphoric acid and 95% can be extracted from here) a total of 11,970 t uranium could have theoretically been recovered. 11,970 t uranium is roughly equivalent to China's total projected uranium demand in 2019-2020. Morocco cannot ramp up production from 27 million t in 2017 [50] and add another 140 million t overnight to provide phosphate rocks to China. It is worth looking at such estimates though to highlight the long term opportunities of recovering uranium from phosphate rocks for the Middle Kingdom.

Table 1. Uranium content in different phosphate rock deposits in China.

Province	Deposit	Uranium content
Anhui	Susong	1 ppm
Guizhou	Kaiyang	8.46-35 ppm
	Guiding	22 ppm
	Pingba	13 ppm
	Tongrenba	60-500, mainly 200-280 ppm
	Zhijin	3.75-43 ppm
Guangxi	Wuming	3.5-69.9 ppm, highest 104 ppm
Hainan	Damao (clasolite)	10.30-53.63 ppm, average 29.71 ppm
	Sanya Damao	5.77-52.63 ppm
Hubei	Baokang	4 ppm
	Huangmailing	2.36-11.6 ppm
	Jingxiang	4.44-7.04 ppm, av. 5.35 ppm
	Jingzhong	2 ppm
	Jingzhou	2 ppm
Hunan	Dayong	34 ppm
	Huaihua	19 ppm
	Huanjingping	18.3-104 ppm, average 60.08 ppm
	Liuyang	15 ppm
	Louxi	0.76-32.8 ppm
	Matian	58 ppm
	Shimen	4 ppm
	Xixi	10.30-32.80 ppm, average 25.34 ppm
Jiangsu	Jinping	12.5-23 ppm
	Xinpu	12 ppm
Jiangxi	Guangfeng	23 ppm
	Shangrao	7 ppm
Shaanxi	Hanzhong Kuanchuan	100-300 ppm, highest 470 ppm
Shanxi	Jinjiahe	8 ppm
	Heijiayan	6 ppm
	Zhongtiaoshan	3-30 ppm
Sichuan	Jinhe	28 ppm
	Shifang	16.71-57.26 ppm, average 31.63 ppm
	Hanyuan Shuitonggou	5.05-15.58 ppm, average 9.29 ppm
	Emei	100-230 ppm, highest 480 ppm
	Leibo	170-480 ppm
	Huidong	100-230 ppm, highest 390 ppm
Yunnan	Anning	13 ppm
	Haikou	34 ppm
	Jianing	22-300 ppm
	Kunyang	11.07-21.48 ppm, 13.26 ppm
	Laogaoshan	26 ppm
	Shangsuanshan	22 ppm
Zhejiang	Pujang	150-300 ppm

4. Conclusions

This work shows that the uranium concentrations in China's phosphate rocks vary widely. Although, the average uranium concentration in China may be low (<30 ppm), deposits with relatively high uranium concentrations above 100 ppm could be identified. These deposits may be the most suitable deposits for uranium recovery from phosphate rocks in China and further detailed sample characterization should be done here if uranium recovery during phosphate fertilizer processing is seriously considered. Besides, the uranium content a number of other factors such as the mineral processing plant size, other accompanying valuable and/or toxic elements, the rock matrix, local environmental regulations, etc. will affect the technical and economic feasibility for uranium recovery at a certain deposit. In addition, to uranium recovery from domestic phosphate rock resources, China may also choose to recover uranium from foreign phosphate rock imports. Today China produces most phosphate rocks at domestic mines. Roughly ¾ of all phosphate rock reserves are found in Morocco though. Importing these phosphate rocks, as may be inevitable in the future, and recover uranium from them during fertilizer production may considerably contribute to China's domestic mining activities and can be considered an equally low-hanging fruit.

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