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Unconventional Uranium in China's Phosphate Rock: Review and Outlook

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ABSTRACT

Some phosphate rock contains elevated concentrations of natural uranium. China is the largest phosphate rock producing country in the world and will soon have the largest uranium requirements in the world as well. Most phosphate rock deposits in China show low uranium concentrations (20–30 mg/kg) so that the recovery of radiotoxic heavy metals is neither economically appropriate nor ecologically necessary. China does, however, also have elevated uranium concentrations (≥90 mg/kg) in phosphate rock deposits in Sichuan and Yunnan. We estimate that China could have recovered nearly 648 metric tU (1.43 million lb U_3O_8) from those mines in 2016. The amount corresponds to 9.7% of the total reported uranium requirements in this year or 39.3% of reported domestic uranium production in 2016. The future uranium recovery potential may be even higher in total numbers (1158 tU or 3.01 million lb U_3O_8 in 2030). The main reason are potentially increasing imports of phosphate rock from large exporting countries such as Morocco that show higher average uranium content. In addition, medium- to lower-grade domestic phosphate rock resources with larger shares of accompanying heavy metals, that include rare earths and uranium, will have to be processed. Although the uranium supply for China is currently not at risk, the supply security could be further increased by obtaining unconventional uranium from domestic and imported phosphate rock.

1. Introduction

China is one of the world's largest producers of nuclear energy. In 2019, the country generated around one-tenth of global nuclear energy. Ambitious plans for the construction of new nuclear power plants as well as indigenous technology being developed suggest a long-term commitment of China towards nuclear energy [1–6]. The rapid construction of nuclear power plants will subsequently increase China's uranium demand. Unconventional uranium recovery could contribute to the uranium supply required for China's nuclear power development, while promoting responsible production (United Nations Sustainable Development Goal 12) and the transition to a circular economy [7–12]. In addition, heavy metal recovery during phosphate rock processing as well as the extraction of other accompanying elements of value, such as

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rare earth elements (REEs), can be considered particularly important in the light of resource efficiency and the sustainable use of mined materials [13–16]. Radiotoxic uranium recovered during phosphate fertilizer production is not being dissipated on agricultural soils from where it may leach into ground water [17–21].

Chen et al. [22] provide a high, a medium and a low demand scenario to predict China's projected uranium requirements that is shown in Fig. 1.

Several other studies (e.g. Refs. [23–28]) are projecting an increased (two- or threefold) uranium demand for China by 2030. It should be noted that China is actively working on several fast reactor concepts to enable a closed fuel cycle as well as options to utilize thorium fuel that may change the uranium demand in the far future [29–31]. These scenarios are not included in the projections presented here. Within this century uranium will most likely be the primary fuel source for nuclear power plants in China.

Most nations deploying nuclear power plants, including China, have limited uranium resources and must import uranium from other countries. The high (future) demand of uranium in China sparked and still sparks discussions regarding the energy supply security of the country [32–47]. Xiao and Jiang [48] have already suggested tapping into presently considered unconventional resources such as uranium associated with phosphates to satisfy China's future nuclear fuel demand. Large shares of unconventional uranium resources globally are associated with phosphate rock [49,50], and China is by far the largest phosphate rock processing country in the world [51].

In the light of resource efficiency and sustainable use of mined materials, recovering uranium and other accompanying elements of value, such as REEs, during phosphate rock processing is desirable [13–15]. Phosphate rock can contain lanthanides (including REEs) and the chemically similar actinides (mostly uranium) in appreciable amounts [52–55]. Techniques to recover uranium from wet-phosphoric acid (WPA), a relevant industrial chemical and an intermediate product during phosphate rock processing to fertilizer, have already been used on an industrial scale in the 1980s in various countries. Solvent extraction processes that have been described in several reviews [56–60] were the predominant choice for uranium recovery from phosphoric acid in the past. While solvent extraction proved technically successful on industrial scale new attempts for more economic uranium recovery based on ion exchange have lately been developed to pilot plant scale by Phosenergy and others. Particularly relevant for this work may be the operation of a full-scale production plant in Taiwan for more than six years [61,62]. Since WPA is a liquid, uranium recovery units can be integrated into the workflow of operating WPA plants without having to change the overall process layout [63]. This is schematically shown in Fig. 2 and can be considered economically attractive when compared with the considerable upfront costs of a traditional uranium mine. With uranium recovery by solvent extraction high recovery rates exceeding 90–95% can be realized and U_3O_8 can be obtained at costs of US$ 44–61 per pound (best estimate for the US [64]), which is slightly above current uranium spot market prices (see Fig. 4). Chinese researchers are actively developing new methods for increasingly efficient recovery of REEs and uranium from WPA during fertilizer production [65–82].

Hu et al. [83] first discussed the opportunity to recover uranium during phosphate fertilizer production in China. Ulrich et al. [84] later estimated that some 710 t natural uranium could have been extracted from WPA during phosphate fertilizer production in China (not including Taiwan) in 2010. The World Nuclear Association (WNA) [85] estimates that some 830 t natural uranium was mined in China that year. Both Hu et al. [83] and Ulrich et al. [84] used average uranium concentrations of 21–31 mg/kg for China as reported by van Kauwenbergh [86], 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. Later results from Ye et al. [87] indicate that uranium concentrations in China's phosphate rock vary significantly from deposit to deposit and can reach concentrations of up to 480 mg/kg in Sichuan Province. The work from Ye et al. [87] focused on the uranium concentration in China's phosphate rock and did not systematically determine the potential quantities of unconventional uranium that can be recovered during phosphate rock processing in China.

The aim of this work is to extend the existing research by analyzing the potential directions for unconventional uranium recovery in China. We aim to determine the quantities of unconventional uranium using openly accessible data that could be recovered during phosphate rock processing in China. Similar assessments were provided for the United States by Kim et al. [64] and Steiner et al. [88], and for the European Union and Argentina by Tulsidas et al. [89] and López et al. [90]. Comparable studies for China do not exist to the best of our knowledge. Additionally, an outlook of potential future uranium recovery from domestic and imported phosphate rock in China is provided.

2. China's Uranium Supply

According to Zhang and Bai [91], China aimed to follow a strategy known as the 'three-third-rule' when it comes to the nation's uranium supply: one-third of the uranium is supposed to be supplied from domestic mining, one-third from direct international trades and one-third from Chinese companies mining abroad. China is not strictly following the 'three-third-rule' today and only used this concept for orientation in the past. Right now, China aims for a portfolio approach in a way that uranium is sourced from wherever it is possible and economically reasonable. Ideally different sources such as the ones of the 'three-third-rule' are used to maximize uranium supply security. Sourcing uranium from abroad does not necessarily result in increased energy dependence. Most countries with a large nuclear reactor fleet such as the United States, France and Japan import most of the uranium resources needed to operate their nuclear reactors. The Herfindahl-Hirschman Index (HHI) can be used to measure market concentrations [92] and thus provide testimony about the market power of individual players in the regarded markets. Market concentrations are expressed as the sum of the squared market shares and represented on a scale from 0 (no concentration) to 10,000 (monopoly). Fig. 3 shows the HHI determined for U_3O_8 production volumes as reported by World Mining Data (WMD) by country. Fig. 4 further contains historic international spot market prices for U_3O_8 as reported by one of the nuclear industry's leading market research and analysis companies UxC, LLC averaged over a year and the HHI.

The United States Department of Justice considers markets in which the HHI is between 1500 and 2500 points to be moderately concentrated, and highly concentrated if the HHI is above 2500 points [93]. The HHI for U_3O_8 production volumes by country, as shown in Fig. 3, from 1984 to 2019 never exceeds 2,500 points, suggesting that the uranium market can be considered a moderately concentrated market. It is worth noting though that it is not countries but often large international mining organizations that trade uranium, so that the HHI on a company level would be lower than on a country level. It is further worth noting that most uranium trades are conducted in non-disclosed long-term contracts. The HHI on a country level, depicted here is, therefore, only of limited value. It is, however, a useful tool to quantify, at least with some degree of certainty, the concentration in the uranium market, which is generally not perceived as high.

Data from UxC [94] depicted in Fig. 5, suggest that China is importing far more than two-thirds of the country's uranium requirements. UxC further reports that China's government policies promote stockpiling of uranium and estimated China's utility inventory to be as high as 171,937 t Ue[1] (447 million pounds U_3O_8e) of which 127,318 t

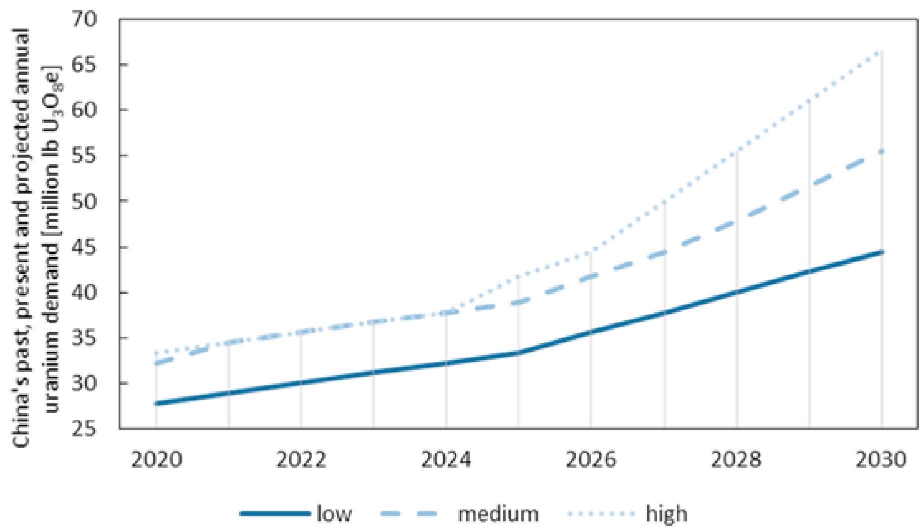

Fig. 1. China's past, present and projected uranium demand from 2018 until 2030, according to Chen et al. [22].

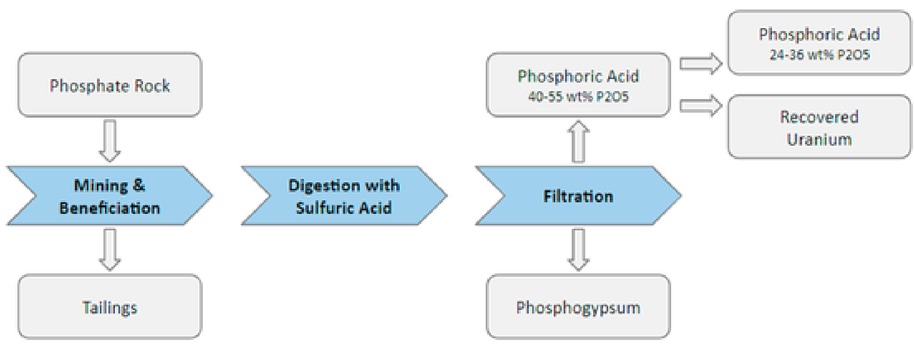

Fig. 2. Phosphoric acid production with uranium recovery by the wet-phosphoric acid (WPA) process.

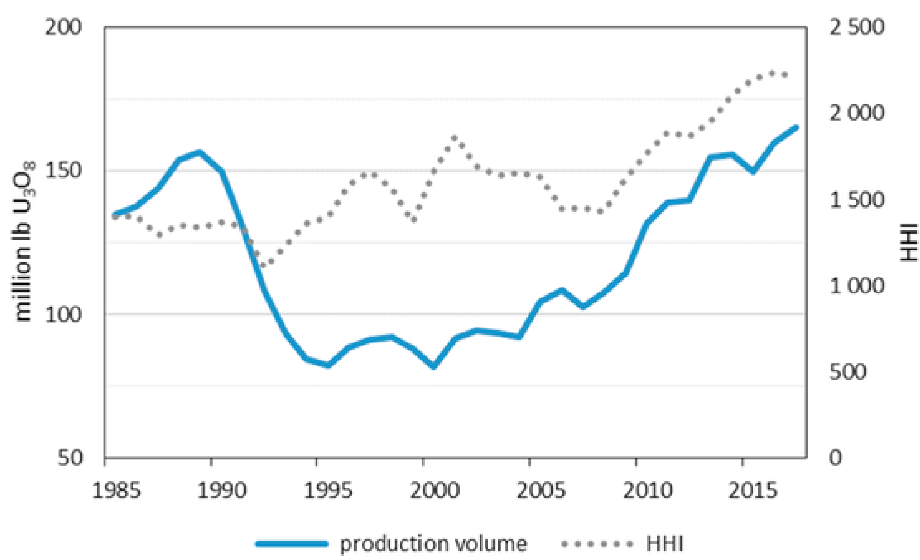

Fig. 3. Historic U_3O_8 production and Herfindahl-Hirschman Index (HHI).

Ue (331 million pounds U_3O_8e) were in form of U_3O_8 in 2018. Approximately half of this material can be considered a "national strategic stockpile" [94].

The presented findings show that China's uranium supply is currently not at risk. This conclusion is further supported by research from Zhang and Bai [91] who report that a large share of domestic uranium resources in China are not explored fully yet. Despite this conclusion, Zhang and Bai recommend an increase of research and development on

[1] Ue = Uranium equivalent.

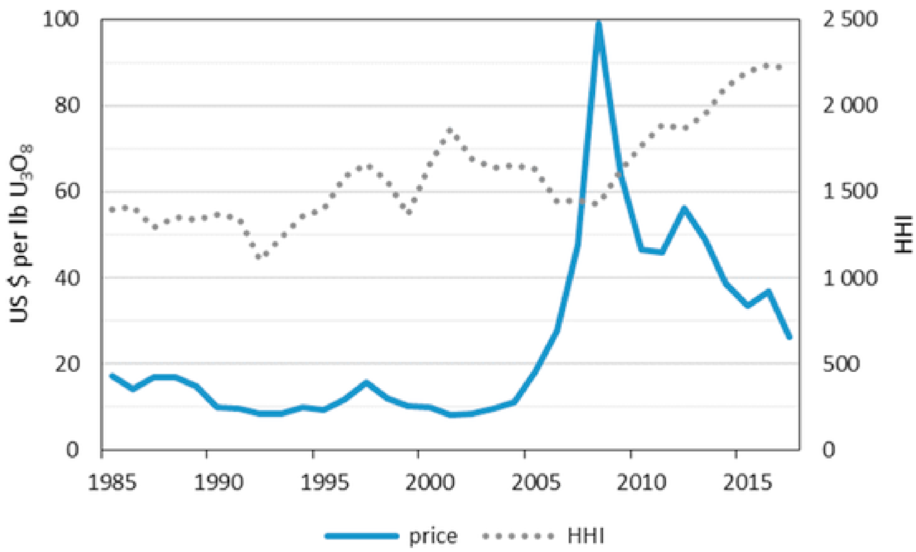

Fig. 4. Historic international spot market prices for U_3O_8 (source UxC) averaged over one year and Herfindahl-Hirschman Index (HHI).

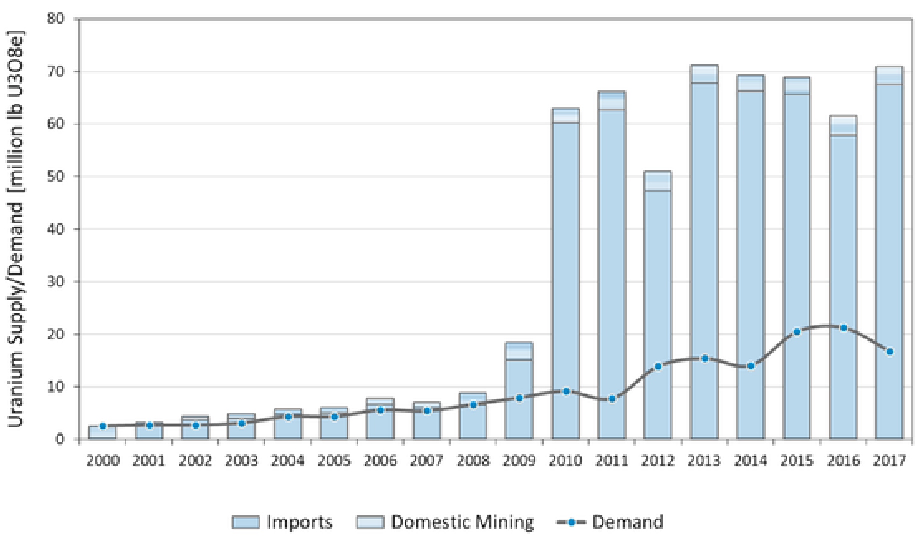

Fig. 5. China's uranium supply/demand balance from 2000 to 2017 [94].

the recovery of uranium from unconventional resources such as phosphate rock and seawater that were both specifically mentioned in the researcher's report.

3. Unconventional Uranium Resources in China's Phosphate Rock

China is by far the largest phosphate rock producing country in the world, mining more than 48% of global phosphate rock in 2018 [51]. China further processes most of the mined phosphate rock domestically so that quantifying the uranium recovery potential from these phosphate rock deposits is reasonable. Uranium has been recovered from WPA on an industrial scale in the past. Not all phosphate rock is, however, processed to WPA so that determining the amount of WPA production in China is a first useful step to further estimate the amount of uranium that could be recovered during phosphate rock processing. Chen et al. [95–97] provide detailed phosphorus flow analysis for China. In Fig. 6 we provide a simplified flow analysis based on data made available by CRUInternational (CRU) to present a brief overview of phosphate rock and WPA production in China.

In 2017 China mined some 24 million tons P_2O_5-equivalent marketable phosphate rock concentrate (PR-M). PR-M refers to beneficiated phosphate rock with phosphorus pentoxide (P_2O_5) content suitable for WPA or elemental phosphorus (P_4) production. Nearly 73% of the P_2O_5-equivalent PR-M in China in 2017 was used to manufacture WPA. A bit less than 12% were lost in the process, more than 8% were used to manufacture elemental phosphorus (P_4), and roughly 7% were directly applied on agricultural soils (DAPR = direct application of phosphate rock) or used to produce nitro phosphate (NP) and single superphosphate (SSP). Of the 73% P_2O_5-equivalent PR-M that were used to produce WPA, approximately 3% were further processed to higher quality intermediate products—namely, defluorinated acid, purified phosphoric acid (PPA) and super phosphoric acid (SPA). Hence, roughly 70% of all mined phosphate rock in China was used for WPA production and could theoretically be considered for uranium recovery in case of traditional uranium extraction from WPA.

A large share of the phosphate rock mined in China does not contain high concentrations of naturally occurring uranium. It is therefore unlikely that uranium can be recovered from this phosphate rock. Realistically uranium recovery will be pursued at deposits with elevated uranium content. These deposits are found in Sichuan and Yunnan province.

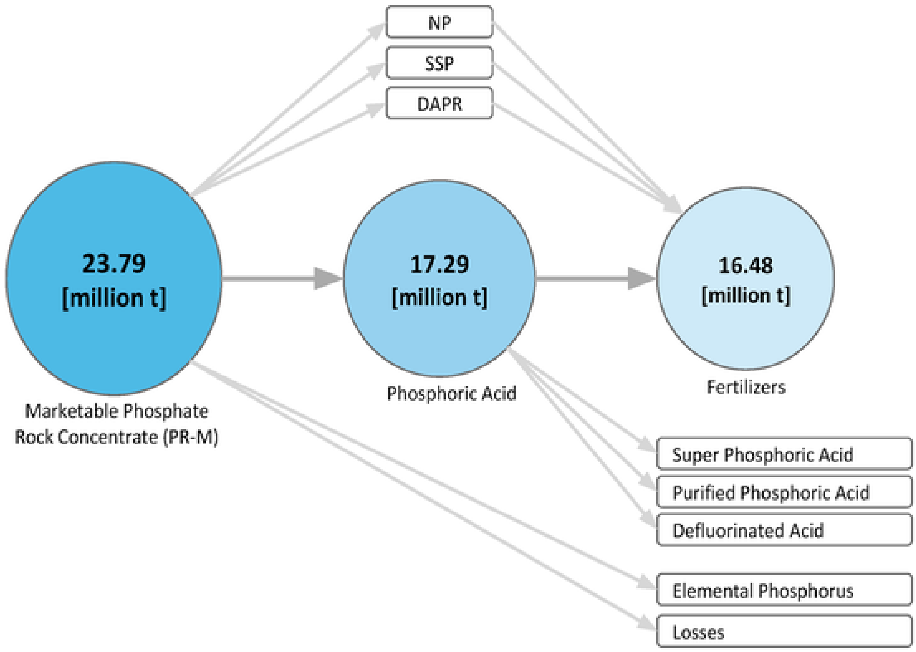

Fig. 6. P_2O_5-equivalent [million tons] processing flow in China in 2017 (source: CRU).

4. The Current Potential to Recover Uranium during Phosphate Rock Production in China

If a cut-off grade of 90 mg uranium per kg phosphate rock is taken into account, as it was done in previous studies [89,90], uranium recovery from mines in Sichuan and Yunnan seems most promising. Using data from CRU that provides WPA production capacities and actual production data for 2016, the potential amount of uranium that could have theoretically been recovered that year in China can be estimated using average uranium concentrations of the regarded deposits as indicated in Table 1.

The Organization for Economic Co-operation and Development (OECD) and the International Atomic Energy Agency (IAEA) report that China produced 1650 tU (4.29 million lb U_3O_8) in 2016 while requiring 6700 tU (17.42 million lb U_3O_8) in the same year to operate her fleet of nuclear reactors [98]. They further estimate that domestic production will remain as high as 1700 tU (4.42 million lb U_3O_8) over the coming years. Uranium recovery from phosphate rock deposits with elevated uranium content of 90 mg uranium per kg phosphate rock as they are found in Sichuan and Yunnan could thus have theoretically provided some 39.27% of domestic uranium production and some 9.67% of total uranium requirements in China in 2016.

Table 1
Potential uranium recovery during phosphate rock production (source: CRU) in China in 2016 applying a cut-off grade of 90 mg uranium per kg phosphate rock.

Province	Average U content [mg/kg][a]	Maximum U content [mg/kg][b]	Potential to recover uranium based on 2016 capacity[c,d]		Potential to recover uranium based on 2016 production data[c,d]	
			[t U]	[million lb U_3O_8]	[t U]	[million lb U_3O_8]
Guizhou	20	21	–	–	–	–
Hubei	8	8	–	–	–	–
Sichuan	92	276	343	0.89	248	0.64
Yunnan	70	137	538	1.40	400	1.04
SUM			**881**	**2.29**	**648**	**1.68**

[a] Based on available 2016 production data by mine from CRU.
[b] 90 mg uranium/kg phosphate rock cut-off grade.
[c] Maximum average uranium content found at one mine side within a province.
[d] Assuming a uranium recovery rate of 0.9 and uranium transfer from phosphate rock in the phosphoric acid stream of 0.9.

5. The Future Potential to Recover Uranium during Phosphate Rock Production in China

Currently, researchers in China and all over the world are actively working on innovative methods to recycle phosphorus [99–101] and increase the efficiency of phosphate rock mining and processing as well as fertilizer application [102–110] with the ultimate goal of reducing phosphate rock mining requirements and environmental impacts associated with phosphate mining and use [111]. It is unlikely that phosphate rock mining in China will be reduced significantly within the next decades [112–115] although environmental regulations are becoming significantly stricter, already resulting in closures of smaller mines today. Li et al. [116] postulate that phosphate rock mining in China will remain fairly constant. This is supported by work from van Vuuren et al. [117] who further estimate that net phosphate rock imports in China will reach 7.6 million t P_2O_5 equivalent (23.5 million t phosphate rock[2]) in 2050 and 8.2 million t P_2O_5 (25.2 million t phosphate rock) in 2100. Cooper et al. [118] further predict that China's phosphate rock production will remain fairly constant between 2020 and 2050 until high-grade phosphate rock deposits are depleted, while the global share of production decreases as a result of a dramatic increase of phosphate rock production in Morocco. Morocco is already the largest exporting country of phosphate rock in the world today. Phosphate rock reserves in Morocco currently account for nearly 75% of the global phosphate rock reserves [118]. It is thus not unlikely that a large share of future Chinese P imports will come from Morocco [119]. These P imports may come in form of phosphate rock, WPA, fertilizers or even food. Most of the phosphate rock processing plants are in close vicinity to the phosphate rock mines inland in the Southwest of China. Countries like the Philippines import all phosphate rock and process it to WPA and subsequently fertilizers [120]. During processing uranium could again be re-

[2] Assuming average P_2O_5 content of 32.5% in the imported phosphate rock.

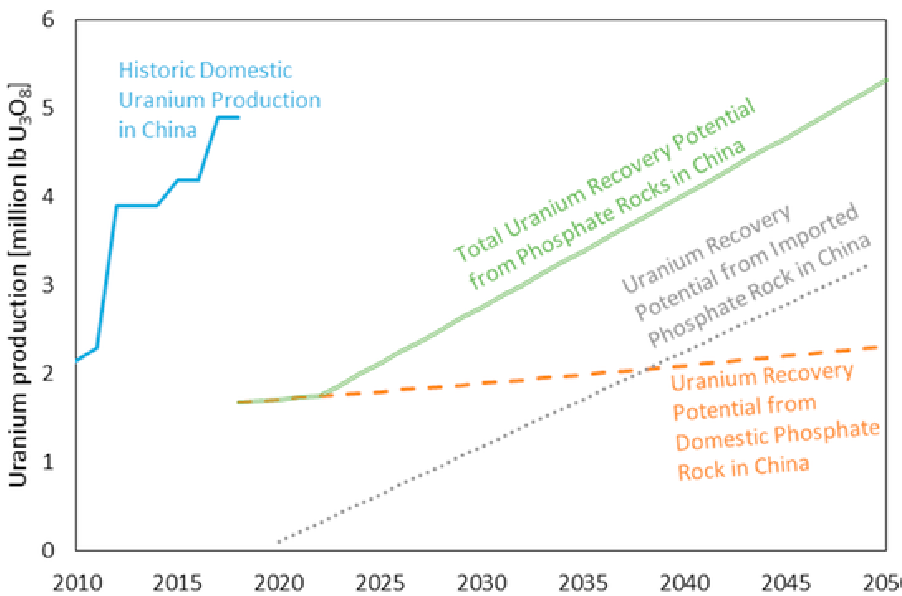

Fig. 7. Historic domestic uranium production and prospective potential future uranium recovery from phosphate rock in China per year.

covered. Since the facilities for phosphate rock processing in China are inland, it is unlikely that phosphate rock will be recovered and further processed in China. Besides, phosphate exporting countries such as Morocco have own interests to process the raw material themselves and thus receive the additional profit of selling a value-added intermediate (WPA) or final (fertilizer/food) product.

Moroccan phosphate rock does, however, show relatively high uranium concentrations that exceed the 90 mg/kg cut-off grade applied earlier and Chinese companies could sign mining agreements on the estimated 6 million t uranium associated with Moroccan phosphates the same way Areva (now Orano) did in 2007 [121] with Morocco's OCP. Phosphate rock could thus be processed in Morocco and recovered uranium could be sent to China. Similar agreements could be envisaged in other countries that have relevant uranium concentrations (>90 mg/kg) in their phosphate rocks and no relevant demand for the uranium of their own.

To estimate potential future uranium recovery from phosphate rock relevant for China we used the future phosphate rock import data from Van Vuuren et al. [117] who estimated that phosphate rock imports to China would reach 7.6 million t P_2O_5 (23.5 million t phosphate rock) in 2050. For a quantitative estimate of the future uranium recovery potential from phosphate rock in China, we postulated a start of these imports in 2020 and a linear increase until the postulated value from Van Vuuren et al. [117] is reached in 2050. We further assumed that for each year (i) the imported phosphate rock (P_i) would have an average uranium concentration (c_i) of 90 mg/kg, that 90% of the uranium found in the imported phosphate rock transfers to phosphoric acid from where it could be recovered with a uranium extraction efficiency (η_i) of 90%. Both industrially proven solvent extraction and upcoming ion exchange technologies for uranium recovery from phosphoric acid show extraction efficiencies exceeding 90%. We further assumed that the share of all imported phosphate rock that is processed to WPA (WPA_i) is like the share previously determined for China (72.67% see Fig. 6). These assumptions can be described as following:

$$\text{Total } U_i = P_i * c_i * \eta_i * WPA_i \qquad \text{(Eq. 1)}$$

Besides uranium recovery from imported phosphate rock, China may also be able to recover uranium during domestic phosphate rock production. Here we started with the quantity of uranium that could have been recovered during phosphate rock processing in Sichuan and Yunnan in 2016 (648 tU, see Table 1) and assumed an increase of 1% every year. The 1% increase is used to account for degrading domestic higher-grade phosphate rock resources as postulated by Zhang et al. [122] and Mudd [123]. Gao et al. [124] further postulate that a number of these lower-grade phosphate rock deposits in China will contain elevated concentrations of REEs and uranium that should be co-extracted. Fig. 7 summarizes the quantitative estimate of the future uranium recovery potential in China.

Historic uranium production until 2018 as reported by OECD/IAEA is shown on the left of Fig. 7 (solid blue line). Potential future uranium recovery from domestic phosphate rock processed in China is shown on the right (orange dashed line) and potential future uranium recovery from imported phosphate rock in China is indicated by the grey dotted line. The total future uranium recovery potential from imported and domestic phosphate rock processed in China is provided by the green compound line. In addition, Chinese companies might also consider uranium recovery during phosphate rock processing abroad. This has not been included in the estimate here now.

The simple calculation estimates that 2148 tU (5.58 million lb U_3O_8) could be recovered from phosphate rock in China in 2050. In this calculation, 1239 tU (3.22 million lb U_3O_8) would come from imported phosphate rock processed in China, and 909 tU (2.36 million lb U_3O_8) would originate from domestic phosphate rock. These amounts of unconventional uranium can be considered relevant (world uranium production amounted to 53,656 metric tU/139.49 million lb U_3O_8 in 2019 [85] and domestic production in China was reported to be as high as 1885 tU/4.90 million lb U_3O_8 in 2018 [98]), but are dwarfed by China's huge future uranium requirements. In 2030, China could theoretically recover 1158 tU (3.01 million lb U_3O_8) from phosphate rock while Chen et al. [22] (see Fig. 1) estimate uranium requirements of 14,508 tU in their low-scenario (8.0% could come from phosphates), 18,135 tU in their medium-scenario (6.4% could come from phosphates), and 21,761 tU in their high-scenario (5.3% could come from phosphates).

6. Conclusions

The uranium market is a moderately concentrated market and China's uranium supply is not at risk. Further spreading potential uranium supply risks by adding more uranium sources such as unconventional uranium resources from phosphates to the supply portfolio can nonetheless be useful. Not all mined phosphate rock can be considered as unconventional uranium resource though as not all phosphate rock is further processed to WPA from which uranium can be extracted relatively easy. Besides, not all phosphate rock shows elevated concentrations of uranium. Uranium recovery from phosphate rock deposits with elevated uranium content larger than 90 mg/kg as they are found in Sichuan and Yunnan could have theoretically provided some 39% of domestic uranium production and some 10% of total uranium requirements in China in 2016. The total amount of uranium that can be recovered from phosphate rock in China will increase over the next decades as China will have to import more phosphate rock from other countries (most likely Morocco) that show much higher (factor four) average uranium concentrations than most phosphate rock presently processed in China. In addition, lower-grade domestic phosphate rock that show larger shares or impurities, particularly REEs and uranium will have to be processed once higher-grade phosphate rock deposits are depleted. We estimate that some 1158 tU can theoretically be recovered from phosphate rock in China in 2030. This value will reach 2148 tU in 2050. In 2030 uranium from phosphate rock could provide 5–8% of the declared uranium requirements in China for that year. We consider these amounts to be significant, and as a result of these relevant amounts of uranium that could theoretically be recovered from phosphate rock in China, we propose to move from loosely following the ‘three-third-rule’ when it comes to the nations uranium supply to loosely adhere to a “four-fourths-rule” were: one-fourth of the uranium is supplied from domestic mining, one-fourth of the uranium is supplied from direct international trade, one-fourth is provided from Chinese companies mining abroad and one-fourth is provided from presently considered unconventional resources, such as phosphate rock, processed in China.

Credit Author Statement

N·H.: Conceptualization and original draft preparation, B.G., D.S., M.B., M.M.: writing—review and editing, L.Z.: visualization. All authors discussed the content, analyzed the data, reviewed, edited the manuscript and ultimately agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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