Information Center
of Ministry of Land
and Resources

BGR Bundesanstalt für
Geowissenschaften
und Rohstoffe

Supply and Demand of Lithium and Gallium

Imprint

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Layout: Jolante Duba

Edition dated: May 2016

ISBN: 978-3-943566-33-8

Titelbild: BGR

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May 2016

Content

Preface

On 19 June 1979, the former State Bureau of Geology, now Ministry of Land and Resources of the People's Republic of China and the Federal Ministry of Economics, now Federal Ministry for Economic Affairs and Energy of the Federal Republic of Germany signed an agreement on a scientific cooperation on geological sciences and techniques.

Main objectives are:

- to cooperate in geoscientific exchange and research in fields of common interest,
- to develop geoscientific knowledge and techniques,
- to strengthen the basis of economic, technical and industrial cooperation among the two economies.

Topics of interest:

- coal (deposits, exploration, coal fires)
- hydrocarbons (geology, laboratory)
- ore deposits of metals and industrial minerals
- engineering and environmental geology
- marine geology
- hydrogeology
- tectonics, geophysics
- geological data bases
- mineral commodities and statistics.

This study on Lithium and Gallium supply and demand falls into the last category and was compiled by the Information Center of the Ministry of Land and Resources of the People's Republic of China (ICMLR) and the Federal Institute for Geosciences and Natural Resources (BGR) of Germany.

The study was presented in October 2015 on the China Mining Congress and Expo 2015 in Tianjin.

Supply and Demand of Lithium

Cui Rongguo, Guo Juan,Yin Liwen

1 Introduction

Throughout the last five decades, the application of lithium can be seen in many traditional industries such as glass and ceramics, metallurgy of non-ferrous metals, air treatment, medicine and organic synthesis, making lithium to the traditional industries as what seasoning is to cuisines. The rapid development of information technology and the electric automobiles in recent years has made lithium battery one of the most robustly growing industries. Consequently, lithium has become an ideal material for light alloy and energy resource of 21th century.

Statistics from the United States Geological Survey (USGS) , the lithium consumption end-use markets in 2013 as follows: glass and ceramics industries, 35 %; battery production, 31 %; lubricating greases, 8 %; continuous casting mold flux powders, 6 %; air treatment, 5 %; polymer production, 5 %; primary aluminum production, 1 %; disposable battery production, 2 % and other uses, 9 %. From 2007 to 2013, lithium consumption experienced a somewhat rapid growth in glass and ceramics industry and battery industry (Table 1).

Table 1: World: Lithium Consumption End-use markets

<table>
<tr><th>Consumption</th><th>2007</th><th>2008</th><th>2009</th><th>2010</th><th>2011</th><th>2012</th><th>2013</th></tr>
<tr><td>Glass and ceramics</td><td>20 %</td><td>18 %</td><td>31 %</td><td>31 %</td><td>29 %</td><td>26 %</td><td>35 %</td></tr>
<tr><td>Batteries</td><td>20 %</td><td>25 %</td><td>23 %</td><td>23 %</td><td>29 %</td><td>35 %</td><td>31 %</td></tr>
<tr><td>Lubricating greases</td><td>16 %</td><td>12 %</td><td>10 %</td><td>9 %</td><td>14 %</td><td>13 %</td><td>8 %</td></tr>
<tr><td>Continuous casting</td><td></td><td>3 %</td><td>4 %</td><td>4 %</td><td>5 %</td><td>8 %</td><td>6 %</td></tr>
<tr><td>Air treatment</td><td>8 %</td><td>6 %</td><td>5 %</td><td>6 %</td><td>4 %</td><td>4 %</td><td>5 %</td></tr>
<tr><td>Primary aluminum production</td><td>6 %</td><td>4 %</td><td>3 %</td><td>6 %</td><td>4 %</td><td></td><td>1 %</td></tr>
<tr><td>Polymers, rubber, etc.</td><td rowspan="2">9 %</td><td rowspan="2">7 %</td><td rowspan="2"></td><td>4 %</td><td>3 %</td><td>3 %</td><td>5 %</td></tr>
<tr><td>Pharmaceuticals</td><td>2 %</td><td>3 %</td><td>3 %</td><td></td></tr>
<tr><td>Others</td><td>21 %</td><td>25 %</td><td>24 %</td><td>15 %</td><td>9 %</td><td>8 %</td><td>9 %</td></tr>
</table>

Source: USGS (2015)

2 Distribution of lithium reserves and resources

2.1 Reserves and resources

Across the globe, lithium can be found mainly in pegmatite type deposit and brine deposit, with lithium-bearing brine resources accounting for a large part of the resources. The pegmatite type deposits are mainly in Australia, Canada, Finland, China, Zimbabwe, South Africa and Congo. Meanwhile, lithium-bearing saline lakes mainly are located in the following countries: Bolivia, Chile, Argentina, China, and the United States.

Statistics from USGS shows that in 2014, worldwide lithium reserves total 13.5 million tons which allow the global lithium production to last for more than 360 years with an annual lithium output of 37,000 tons. Among all the countries, Chile tops the list with a reserve volume of 7.5 million tons, followed by China (3.5 million tons), Australia (1.5 million tons) and Argentina (850,000 tons) (Table 2). Statistics vary by different organizations. SNL MEG in 2013 reported that the total lithium reserves on earth added up to around 23.4 million tons, with which the lithium production can last 640 years with an annual production output of 37,000 tons. Meanwhile, in the same year, Roskill reported the total lithium reserved to be on the order of 20.8 million tons.

Table 2: World: Lithium reserves (thousand tons, lithium content)

Country	SNL,2013			Roskill, 2013	USGS, 2014
	Lithium Extracted From minerals	Lithium Extracted From saline-lake	Total		
Chile		7,500	7,500	7,300	7,500
Bolivia		5,500	5,500	5,500	
China	750	2,750	2,750	3,900	3,500
Argentina		2,550	2,550	2,700	850
Australia	970		970	505	1,500
Serbia	850		850		
Congo (DR)	1,000*		1,000*	310	
Russia	1,000*		1,000*		
Canada	256	108	364	204	
Austria	100		100		
Brazil	46		46	50	48
United States		38	38	169	38
Zimbabwe	23		23	25	23
Finland	14		14	6	
Portugal	10		10	10	60
Afghanistan				150	
World Total	**5,069**	**18,338**	**23,407**	**20,080***	**13,500**

* estimate

Source: SNL (2014), Roskill (2013), USGS (2015)

In 2014, USGS estimated that the global lithium resources totaled 39.5 million tons. Bolivia ranks the first with 9 million tons of resources, followed by Chile (7.5 million tons), Argentina (6.5 million tons), United States (5.5 million tons), China (5.4 million tons) and Australia (1.7 million tons) (Table 3). SNL MEG (2013) reported similar result estimating the lithium resources add up to 39.15 million tons.

Table 3: World: Lithium resources (thousand tons, lithium content)

Country	USGS, 2014	SNL, 2013
Chile	7,500	7,500
Bolivia	9,000	9,000
China	5,400	5,400
Argentina	6,500	6,500
Australia	1,700	1,700
Serbia	1,000	1,000*
Congo (DR)	1,000	1,000*
Russia	1,000	1,000*
Canada	1,000	364
Austria		100
Brazil	180	64
United States	5,500	5,500
Zimbabwe		57
Finland		14
Portugal		60
World Total	**39,500**	**39,151**

* estimate
Source: USGS (2015), SNL (2014)

2.2 Changes of reserves and resources

In recent years, an increasing number of projects prospecting and developing lithium resources have been carried out across the world, leading to the discoveries of lithium deposits and an increase of lithium reserves and resources. According to USGS, the global lithium resources have increased 14 million tons from 25.5 million tons in 2009 to 39.5 million tons in 2014, a 54.9 % increase in five years. During the five years, the global lithium reserves climbed from 9.9 million tons to 13.5 million tons, 36.4 % up. China and Australia are front runners in the growth of reserves with a 1.6 fold growth and 5.5 fold growth respectively (Table 4).

Table 4: World: Changes in lithium reserves (thousand tons, lithium content)

Country or region	2009	2010	2011	2012	2013	2014
Argentina	800	850	850	850	850	850
Australia	580	580	970	1,000	1,000	1,500
Brazil	190	64	640	46	46	48
Chile	7,500	7,500	7,500	7,500	7,500	7,500
United States	38	38	38	38	38	38

Country or region	2009	2010	2011	2012	2013	2014
Canada	180					
China	540	3,500	3,500	3,500	3,500	3,500
Portugal	10	10	10	10	60	60
Zimbabwe	23	23	23	23	23	23
World total	**9,900**	**13,000**	**13,000**	**13,000**	**13,000**	**13,500**

Source: USGS (2015)

2.3 Regional distribution of reserves and resources

Around 70 % of lithium is consentrated in “the lithium triangle”. In terms of lithium reserves, Chile, rich in saline lake lithium reserves that accounts for almost one third of the global volume, ranking the first. Bolivia, making up 24 % of the total, comes next, followed by China with 3.5 million tons of lithium reserves. Argentina, whose saline lake lithium reserves make up 11 %, ranking the fourth. As for the lithium resources, 59 % of the reserves located in “the lithium triangle” countries (Chile, Bolivia and Argentina) with 14 % in China, and another 14 % in the United States (Figure 1).

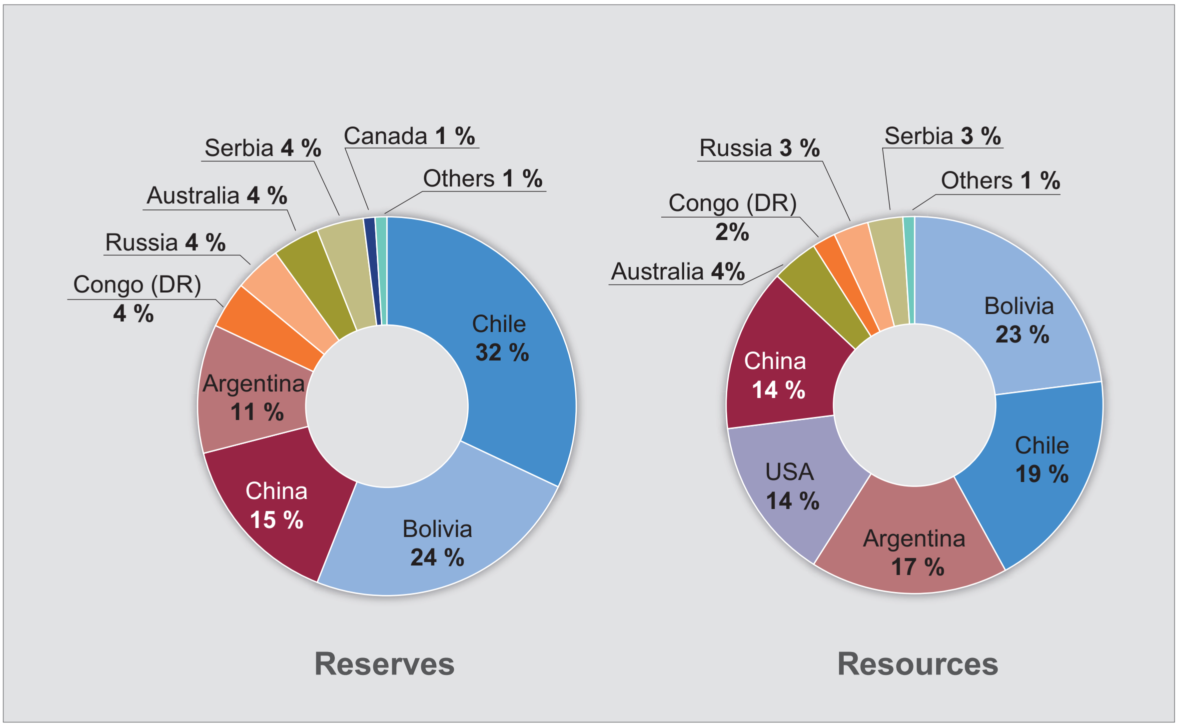

Figure 1: Regional distribution of lithium reserves and resources, 2013

2.4 Reserves and resources in China

According to Ministry of Land and Resources, P.R.C., in 2014, Li_2O reserves in China added up to 420,000 tons, and the reserves and resources totaled 2.94 million tons, mainly located in Sichuan, Jiangxi, Hunan and Xinjiang. LiCl reserves totaled 3.75 million tons, and the reserves and resources reached 19.07 million tons, which are concentrated in Qinghai, Hubei, Sichuan, Xinjiang and Tibet. Spodumene reserves in China totaled 27,000 tons, and the reserves and resources totaled 87,000 tons, located in Jiangxi, Xinjiang and Sichuan. Lepidolite reserves amounted to 10,000 tons, and the reserves and resources amounted to 10,000 tons, which are mainly located in Jiangxi.

3 Lithium production

3.1 Changes of lithium production

The lithium production around the world has been on the increase from 2004 to 2013, discounting a fall in 2009. In 2013, the global mine production reached 37,000 tons (Li), or 197,000 tons of lithium carbonate, a 3.5 % year-on-year increase (see Figure 2).

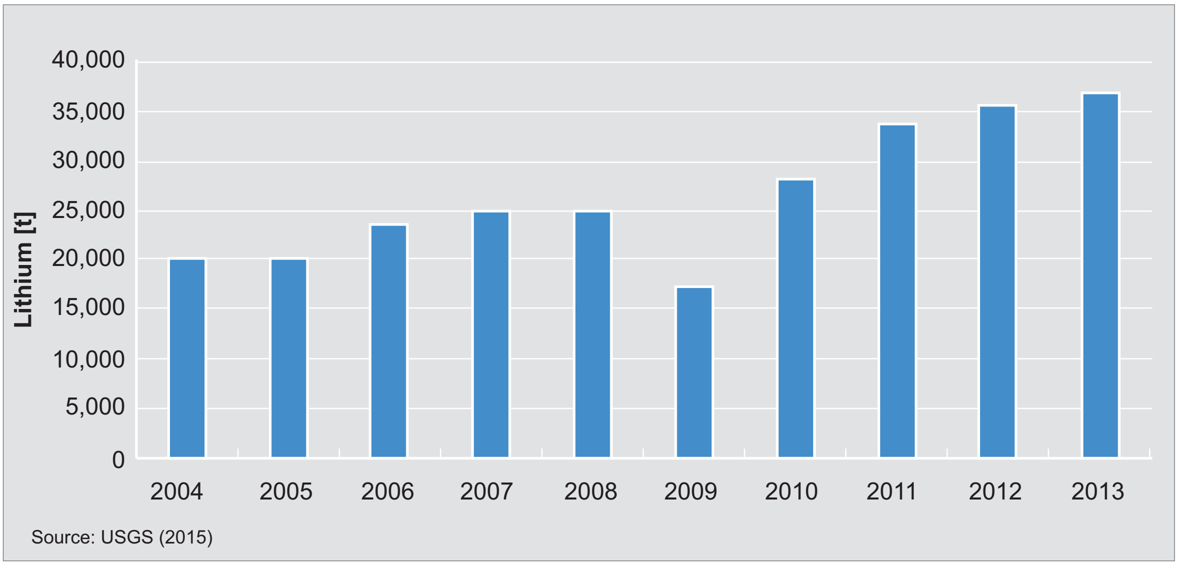

Figure 2: Global lithium production

3.2 Regional distribution of lithium production

Global lithium productions are mainly concentrated in Chile, Argentina, Australia and China. In 2013, the lithium production of the four countries totaled 27,000 tons (Li), accounting for 76.9 % of the global production (Table 5).

Table 5: World: Lithium minerals and brines production

Country	Lithium mineral products	2008	2009	2010	2011	2012	2013
Argentina	Lithium carbonate	10,000	8,574	11,178	10,000	9,700	9,500
	Lithium chloride	7,800	4,279	6,644	4,480	4,350	4,200
	Total (lithium)	3,170	2,309	3,184	2,610	2,533	2,471
Australia	Spodumene	239,528	197,482	295,000	421,396	456,921	421,000
	Total (lithium)	6,280	4,400	9,260	12,500	12,800	12,700
Brazil	Concentrate	14,460	15,929	15,733	7,820	7,084	8,000
	Lithium	160	160	160	320	150	400
Canada	Spodumene*	22,000	10,000	–	–	–	–
	Total (lithium)	690	480				20,00*
Chile	Lithium carbonate	48,469	25,154	44,025	59,933	62,002	52,358
	Lithium chloride	4,362	2,397	3,725	3,864	4,145	4,091
	Lithium hydroxide	4,050	2,987	5,101	5,800	5,447	4,197
	Total (lithium)	10,600	5,620	10,510	12,900	13,200	11,200
China	Lithium carbonate	17,500	20,000	21,000	22,000	24,000	25,000
	Total (lithium)	3,290	3,760	3,950	4,140	4,500	4,700
Portugal	Lepidolite	34,888	37,359	40,109	37,534	20,698	38,000
	Total (lithium)	570	–	800	820	560	570
Zimbabwe	Petalite, spodumene	50,000	50,000	47,000	48,000	53,000	50,000
	Total (lithium)	400	400	470	470	1,060	1,000
World	**Lithium**	**25,160**	**17,809**	**28,334**	**33,760**	**34,803**	**35,041**

* estimate

Source: USGS (2015), USGS (2013), Jaskula (2015)

3.3 Major lithium producers

In terms to the global lithium carbonate distribution and production capacity, SQM, Talison Inc.(51 % of whose share is held by Tianqi Lithium Inc.), Rockwood Corp. and FMC are major producers, contributing to over 80 % of the global volume. The next two years will witness a steady growth of lithium production capacity of the world's lithium as they start new projects and continue to work on the projects in progress. As for the production of lithium carbonate, SQM and FMC have an annual growth rate of nearly 10 %. Rockwood, 25 %. The two-stage capacity expansion of Greenbush's chemical plants made it possible for Talison to achieve a capacity of around 740,000 tons of lithium concentrate (equivalent to 110,000 tons of lithium carbonate equivalent) in 2012.

Nearly 70 % of the global lithium mineralss in 2013 is supplied by Galaxy Resources and Talison, which accounted for 65 % of the global volume. Meanwhile, as high as 92 % of the supply of saline lake lithium is provide by SQM, Rockwood and FMC. As a result, lithium giants across the world have a monopoly on the supply of lithium (Figure 3).

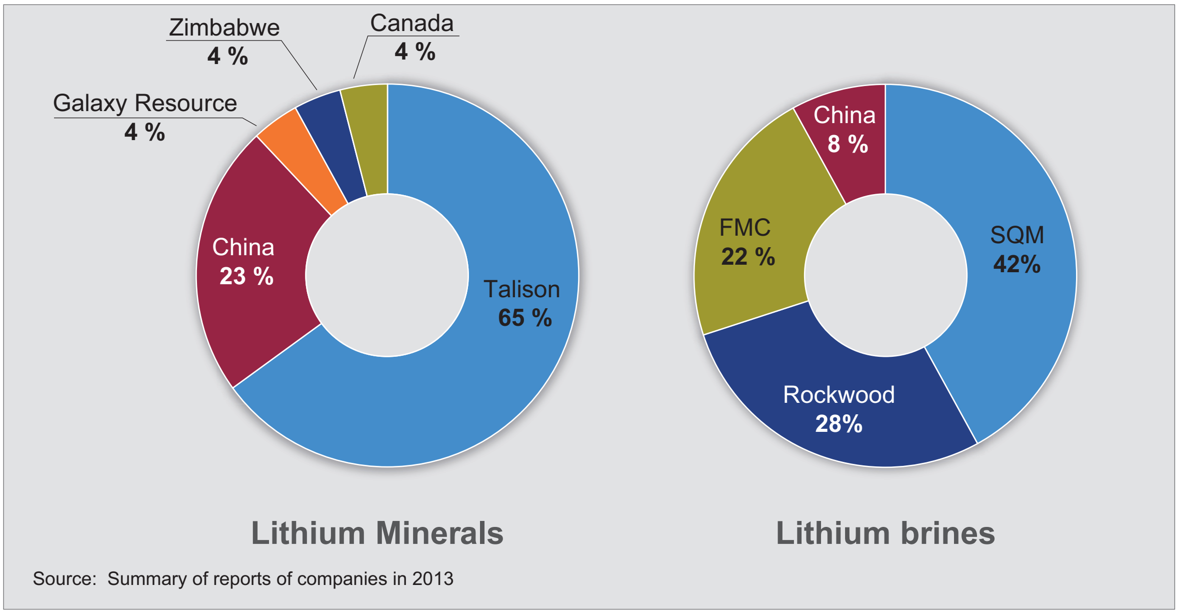

Figure 3: Global supply of lithium minerals and brines, 2013

3.4 Lithium production in China

Despite the fact that China is the third lithium-richest country, China lithium production accounts for mere 5 % of the global. However, the production of both lithium brines and minerals has been on the growth in recent years (Table 6). 80 % of lithium is from minerals.

Table 6: China: Production of lithium (Gross weight, metric tons)

	Brines (Li_2CO_3)	Minerals	Total Prod. (LCE)*
2003	–	35,000	4,328
2004	100	36,000	4,551
2005	200	37,000	4,775
2006	300	37,000	4,875
2007	500	38,000	5,199
2008	2,500	40,000	7,446
2009	7,000	62,000	14,666
2010	5,500	81,000	15,516
2011	5,000	91,000	16,252
2012	4,000	100,000	16,365

* Based on an average Li_2O content of 5.0 % in lithium minerals produced

Source: BGS, Roskill (2013)

4 Lithium supply and consumption

4.1 Lithium consumption

Lithium consumption across the world totaled 132,000 tons LCE in 2011. In 2012, driven by the development in lithium-ion battery industry, the demand for lithium increased significantly to 147,000 tons, a year-on-year increase of 11.4 %. In 2013, the growth of global lithium consumption continued, with the global consumption reaching 160,000 tons, a year-on-year increase of 8.8 % (Table 7).

Table 7: World: Lithium consumption

–	2010	2011	2012	2013	2014*
Consumption	113,000	132,000	147,000	160,000	162,000

* estimate

Source: Antaike

4.2 Lithium consumption markets

The battery industry is the biggest driver for the global lithium consumption, accounting for 31 % of the total consumption in 2013, followed by glass and ceramics and lubricating greases (Figure 4). Lithium consumption maintained a 6 % annual growth rate from 2000 to 2013.

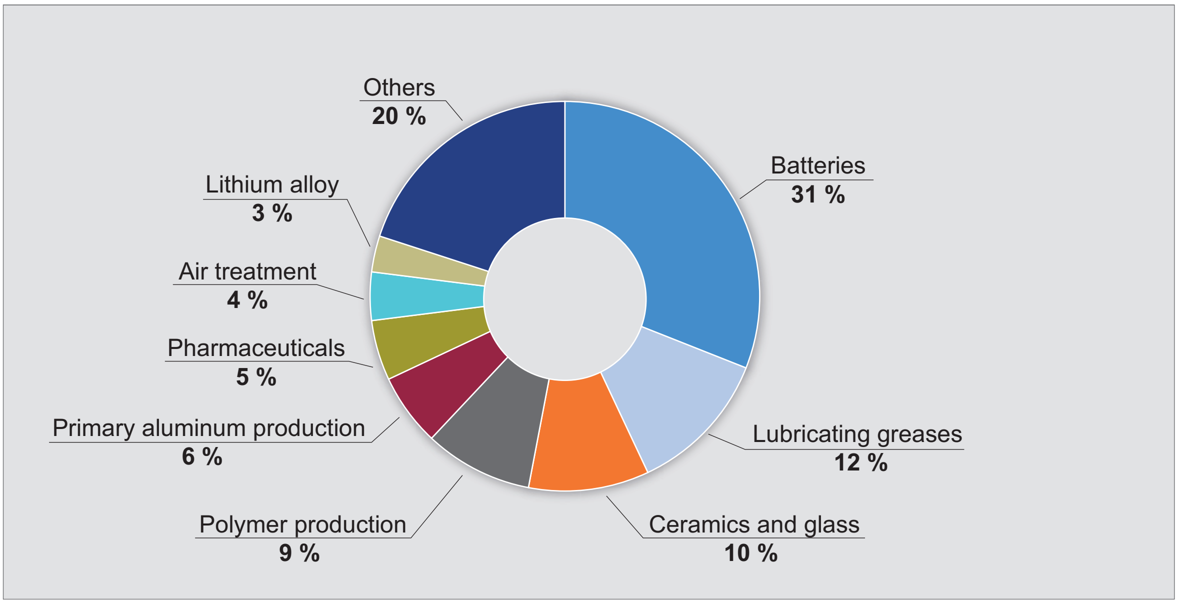

Figure 4: Global lithium consumption in 2013

4.3 Trade

The international lithium trade dominates in lithium carbonate. In 2012, global lithium export reached 79,064 tons LCE. Chile and Argentina have limited demand for lithium carbonate but they have been major exporters of lithium carbonate. Lithium carbonate export from these two countries accounted for over 80 % of the world (Table 8).

Table 8: World: Total exports of lithium carbonate (Gross weight, metric tons)

	2005	2006	2007	2008	2009	2010	2011	2012
Chile	41,832	38,682	41,125	42,586	22,443	40,896	48,248	55,899
Argentina	7,300	8,028	7,794	10,755	8,578	11,296	9,898	9,399
Belgium	5,017	4,962	4,873	3,531	3,028	4,455	4,467	5,022
China	1,366	3,174	3,,107	2,,490	2,000	2,655	5,362	2,973
United States	5,282	4,336	4,211	4,592	1,915	2,277	2,120	2,073
Germany	2,991	2907	2,705	2,290	1,881	2,556	2,921	2,258
Other	3,426	6,534	1,646	1,905	1,531	1,762	1,994	1,440
Total	**67,214**	**68,623**	**65,461**	**68,149**	**41,377**	**65,898**	**75,010**	**79,064**

Source: GTIS (2015)

Global imports of lithium carbonate reached 80,623 tons in 2012. There are more than 9 countries imported more than 2000 tons (Table 9).

Table 9: World: Total imports of lithium carbonate (Gross weight, metric tons)

	2005	2006	2007	2008	2009	2010	2011	2012
Japan	10,001	14,521	13,553	13,194	8,023	14,029	15,089	12,753
United States	19,340	16,068	15,547	15,775	9,263	9,495	14,465	13,232
Korea	2,335	2,540	3,855	5,247	5,142	7,987	11,425	13,762
China	8,572	6,365	3,832	4,306	2,389	6,398	8,250	13,622
Belgium	6,320	5,342	5,891	4,410	3,410	4,181	7,768	7,204
Germany	8,097	7,908	8,131	7,142	4,493	6,795	5,738	6,058
Spain	1,553	828	1,819	3,994	2,825	3,239	3,338	2,476
France	1,439	1,227	1,290	1,251	1,172	1,137	2,792	1,756
Russia	2,955	938	873	891	545	696	2,110	2,200
Other	8,732	9,239	10,243	10,150	7,030	8,182	9,287	7,560
Total	**69,344**	**64,976**	**65,034**	**66,360**	**44,292**	**62,139**	**80,262**	**80,623**

Source: GTIS (2015)

Spodumene concentrate is predominantly exported from Australian to China, Belgium, Germany and the United States. Meanwhile, petalite concentrate produced in Zimbabwe is exported mainly to South Africa, and the products are sold mainly to Asia and Europe. Lithium minerals from Protugal and Brazil is mainly exported to China and Spain, respectively (Table 10). Trade in lithium brine is much less, and SQM, the main exporter in Chile, exprots lithium chloride brine to Ganfeng Lithium of China with limited quantity (Table 11).

Table 10: World: Lithium minerals export (Gross weight, metric tons)

	2005	2006	2007	2008	2009	2010	2011	2012
Australia	14,5472	435,689	243,662	236,441	225,761	324,115	402,688	514,620
Zimbabwe	17,805	236,80	26,769	26,424	35,783	41,015	35,453	38,398
Portugal	120	625	612	372	82	1,401	712	600
Brazil				211	150	30	28	7

Source: GTIS (2015)

Table 11: Chile: Exports of lithium chloride brine from SQM to China (Gross weight, metric tons)

	2005	2006	2007	2008	2009	2010	2011	2012
Net weight	–	–	2,260	6,638	8,129	9,220	16,534	16,800
LiCl/ %	–	–	33	33	33	33	33	33
Lithium chloride	–	–	746	2,190	2,683	3,043	4,752	4,828

Source: GTIS (2015)

4.4 Lithium consumption in China

China Lithium Association estimates that China has consumed 35,800 tons of LCE in 2010, a year-on-year growth of 44 %. In 2012, the rapid development of small lithium ion battery industry drove the total lithium consumption to 55,000 tons of LCE, a 49.4 % year-on-year increase. In 2013, lithium consumption goes up to 63,000 tons of LCE, accounting for 39 % of the global (Table 12).

Table 12: China: Lithium consumption (metric tons, LCE)

	2010	2011	2012	2013
Consumption	35,800	36,800	55,000	63,000

Source: China Lithium Association

The battery industry plays a significant role in China's consumption of lithium. In 2013, end-use markets are estimated as follows: batteries, 42 %; lubricating grease, 18 %; glass and ceramics, 15 %; medicine, 10 %; dyes and adsorbent, 6 %; catalyst 5 %; and other uses, 4 % (Table 13, Figure 5).

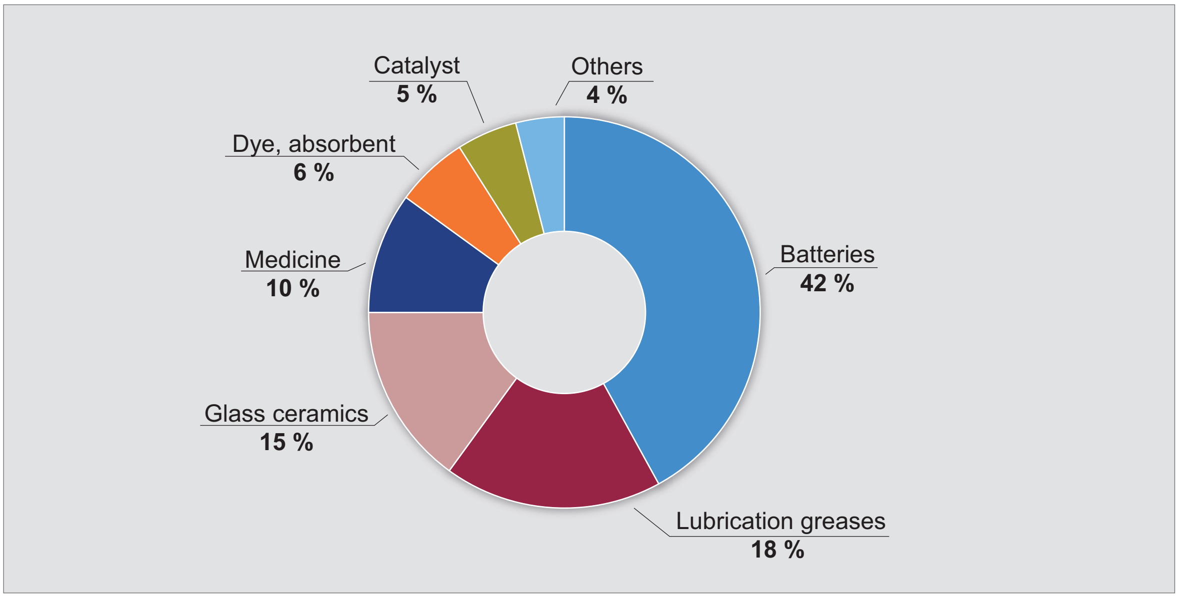

Figure 5: 2013 Lithium consumption end-use markets in China

Table 13: China: Lithium consumption end-use markets (metric tons, LCE)

End-use market	2010	2011	2012	2013
Batteries	9,670	12,140	18,150	27,090
Lubricating greases	4,300	40,50	8,800	11,340
Glass and ceramics	6,090	6,620	5,500	9,450
Pharmaceutics	1,430	740	2,200	6,300
Dye, adsorbent	1,070	370	3,850	3,780
Catalyst	1,430	3,500	3,850	3,150
Other	11,810	9,750	12,650	2,520

Source: China Lithium Association

China is a major player in the trade of lithium products, along with Japan and South Korea is the world's leading producer of lithium-ion batteries, and that Japan, South Korea have set up plants in China, giving a further boost to China demand for lithium. The trading of lithium carbonates assumes a prominent role in the global lithium trade, and China is of no exception (Table 14, 15). Imports from Chile over 95 %; from Argentina accounting for 3 % to 5 %. Each year, China imports 250,000 tons to 300,000 tons of spodumene concentrate from Australia.

Table 14: China: Lithium export (Gross weight, metric tons)

Products	2010	2011	2012	2013	2014
Lithium hydroxide	2,455	4,381	3,460	4,215	6,167
Lithium chloride	245	260	353	404	404
Lithium carbonate	2,655	5,362	2,973	1,250	2,463

Source: China Customs

Table 15: China: Lithium import (Gross weight, metric tons)

Products	2010	2011	2012	2013	2014
Lithium hydroxide	49	76	488	239	149
Lithium chloride	4,241	2,561	2,753	2,557	6,090
Lithium carbonate	6,398	8,250	13,622	13,681	13,601

Source: China Customs

4.5 Lithium price

The price of lithium carbonate rises year after year due to the more and more demand of lithium (Figure 6).

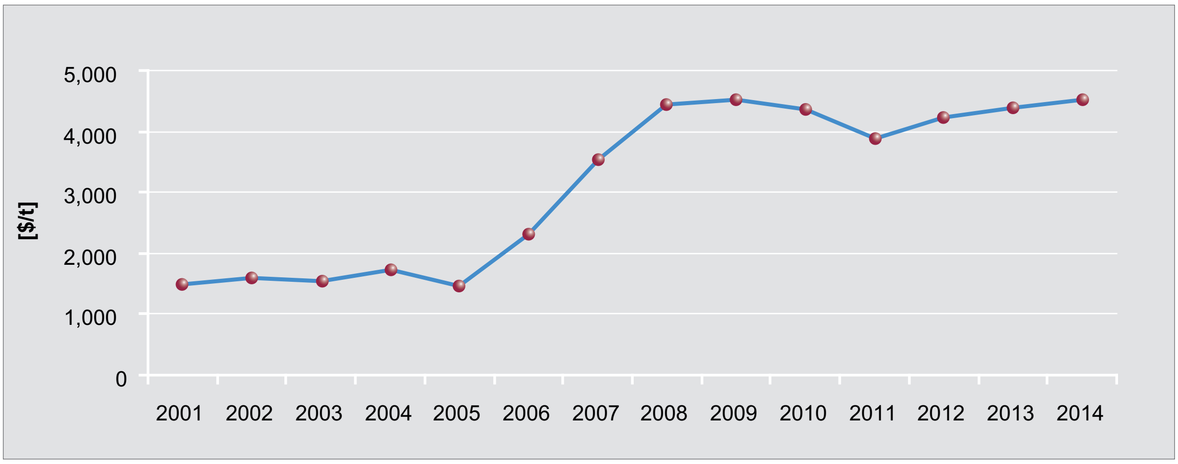

Figure 6: Price of lithium carbonate in USA

5 Outlook for lithium supply and demand

To cope with global issues such as shortage of fossil energy and climate change, our society must develop clean energy. To this goal, governments across the globe are striving to the development of renewable energy generation and emerging industries such as electric automobile. It is projected that the next ten years will witness a growth in the demand for lithium around the world.

5.1 Outlook for lithium demand

The global demand for lithium will increase at an average annual growth rate of more than 10 % in the following ten years. Currently, battery industry is the most lithium-demanding, followed by glass, ceramics and lubricating greases. The demand of battery industry, increasing by over 10 % each year, is climbing up at the fastest compared to others. The demand for lithium of lubricating greases industry grows by 3.5 %, and the glass and ceramics, 3 % to 5 %.

The Chilean company signum Box predicts that the demand for lithium-ion battery industry will experience a robust growth. In 2020, the global lithium demand will be about 285,000 tons (LCE, unless otherwise noted). The lithium-ion battery industry will need about 150,000 tons, or 52.6 % of total demand. In 2025, the global demand will be around 405,000 tons, 61.2 % of which (around 250,000 tons) will be consumed by the battery industry (Figure 6, 7).

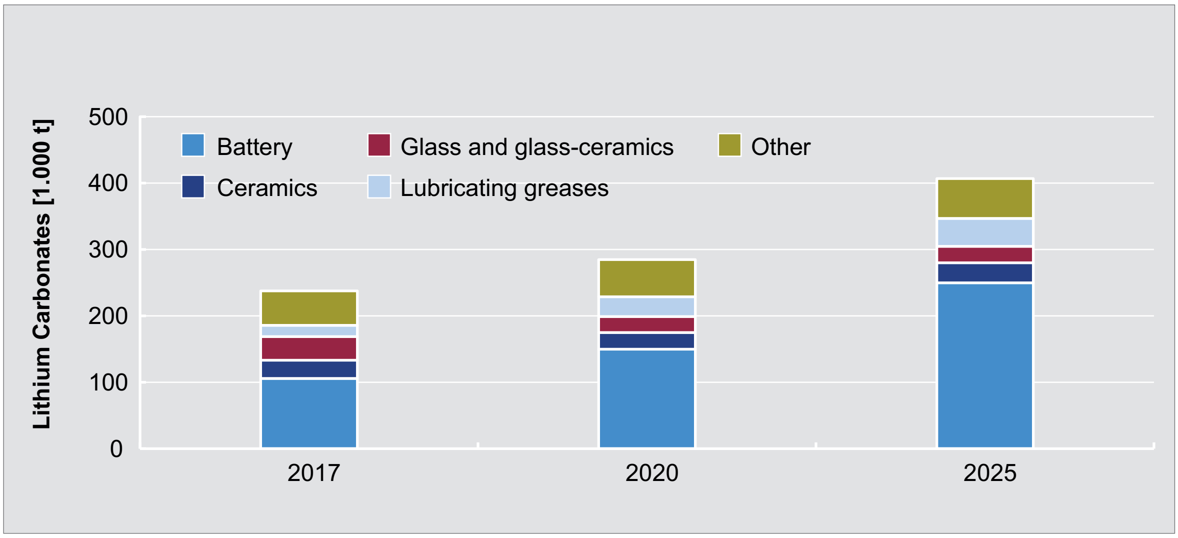

Figure 7: Outlook for lithium demand

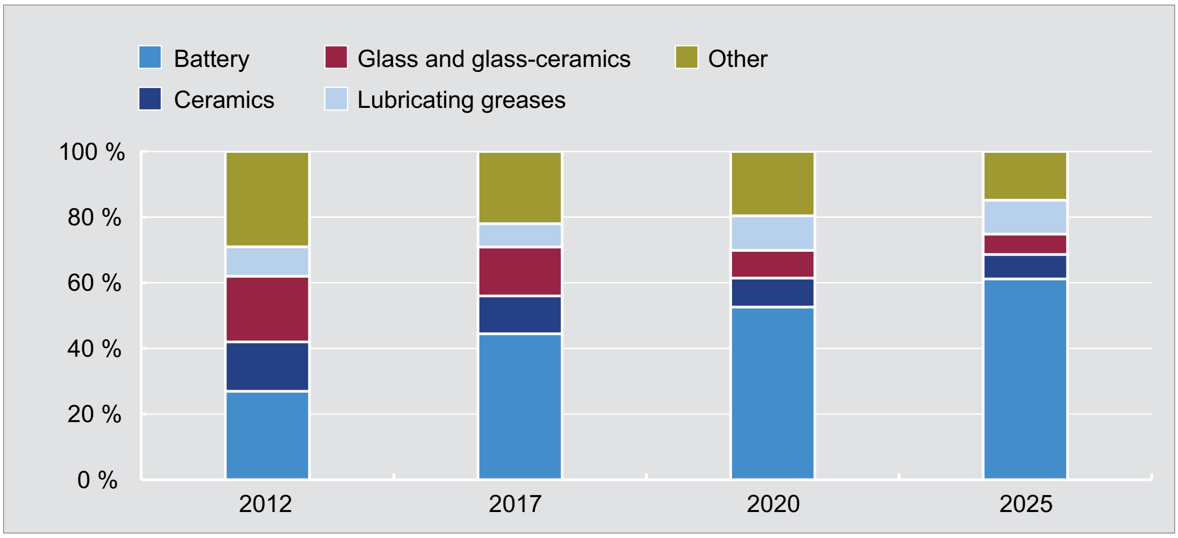

Figure 8: Outlook for lithium consumption by end-use

China's economy will be developing at medium-to-high growth rate in future. The government is actively promoting the development of clean energy economy, energy production and consumption revolution. China is the biggest market with the fastest-growing potential demand. In the next ten years, industries including new energy vehicles, energy-storing battery, electronic products and electric tools will have an increase of demand, which will further boost the demand for lithium. It is estimated that in 2017, China's lithium demand will reach 104,800 tons. In 2020 and 2025, the number will be 131,800 tons and 187,770 tons respectively (Figure 8, 9).

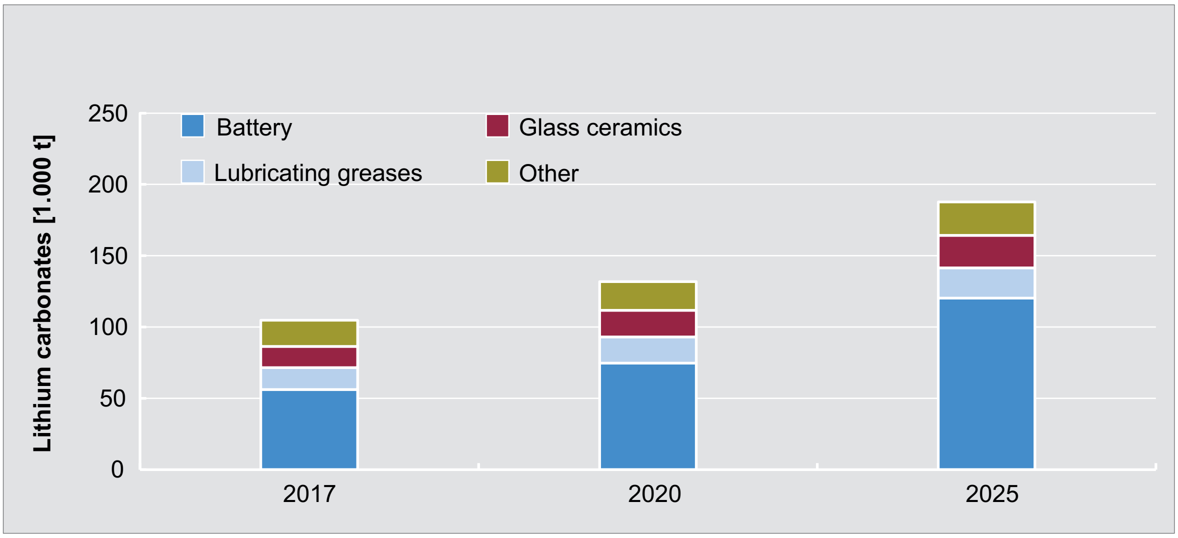

Figure 9: Outlook for China lithium consumption

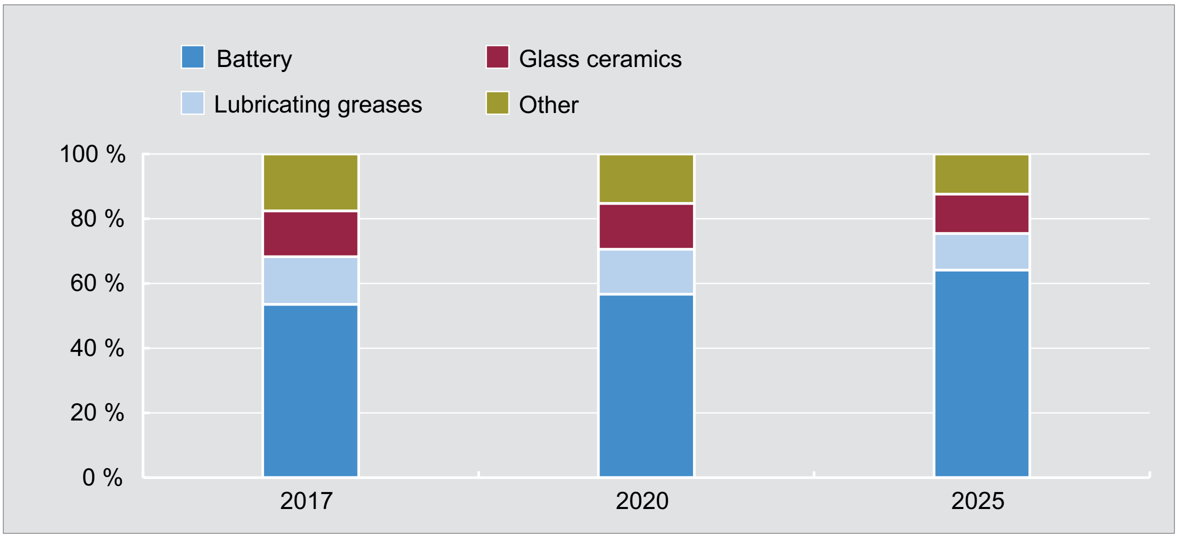

Figure 10: Outlook for China lithium consumption by end-use

5.2 Outlook for lithium supply capacity

With the strong growth in the global demand for lithium, there are more than 20 projects which are expanding or in progress. It is predicted that by 2017, global production capacity for lithium brines will reach 271,000 t/a and that of lithium minerals will be 280,000 t/a, adding up to a total of 551,000 t/a. It is estimated that global lithium production capacity will reach 730,000 t/a by 2025.

Table 16: World: Production capacity of lithium (LCE, t/a)

Products	Current capacity	Expanded capacity	New projects	Newly expanded capacity	Production capacity in 2017	Newly expanded capacity	Production capacity in 2025
Lithium brine	127,000	88,050	4	56,000	271,000	76,000	347,500
Lithium minerals	183,000	22,500	4	75,000	280,000	100,500	380,500
Total	**31,000**	**110,550**	**8**	**131,000**	**551,000**	**176,500**	**728,000**
Lithium compound	199,000	136,000		128,000	463,000		
Lithium concentrate	72,000	48,000	8	72,000	192,000		

It is predicted that by 2017 the production capacity for lithium compounds will reach 463,000 t/a. There are 271,000 tons lithium compounds made from saline lake with a cost of US$1,500/t to US$3,000/t, and 192,000 tons from concentrate with a cost of US$3,200/a to US$4,500/a. Provided that the price of lithium carbonate is higher than US$4,500/t, the lithium brine will reach 240,000 tons with 130,000 tons produced by producing companies and 110,000 tons produced by the projects which are expanding or in progres. If the price of lithium carbonate is higher than US$5,000/a, then the production capacity of lithium compounds from concentrate is expected to be 130,000 t/a; while if the price is lower than US$5,000/t, the production capacity is expected to be less than 70,000 t/a (Figure 10).

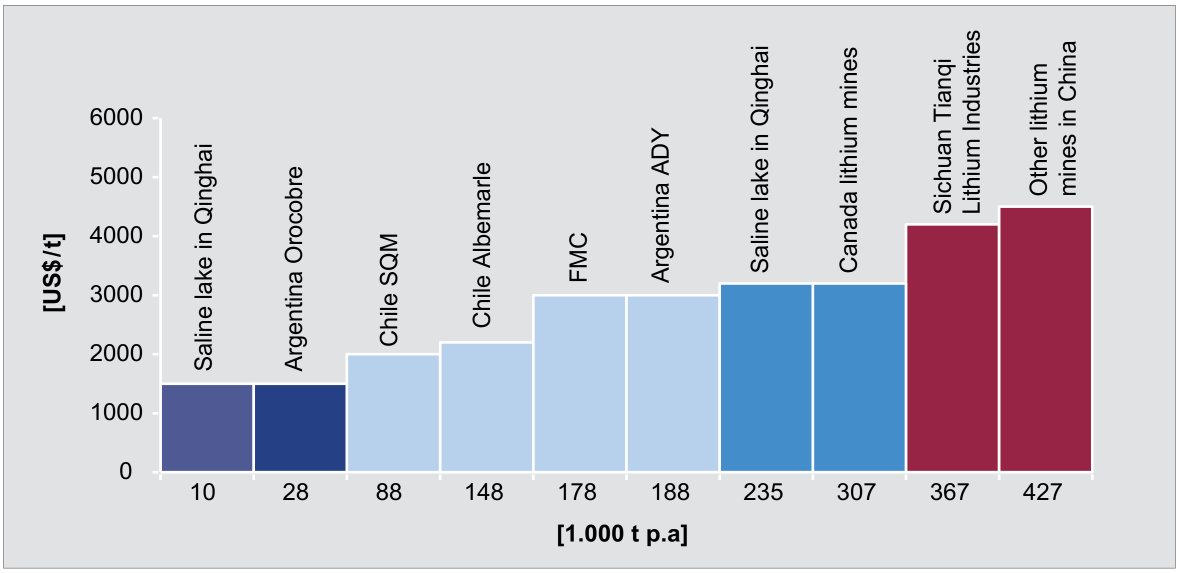

Figure 11: Production capacity and cost of lithium carbonate

5.3 China lithium supply capacity

It is estimated that in 2017, the capacity of lithium will total 228,000 t/a, with 72,000 t/a form brines and 156,000 t/a from lithium minerals. The capacity of lithium compounds is estimated to be 192,000 t/a, 62.5 % of which (or 120,000 tons) is from lithium concentrate. In China, lithium compounds from concentrate will cost over US$4,200/t. If the price of lithium carbonate is higher than US$5,000/t, then the capacity of lithium compounds from minerals is estimated to 80,000 to 90,000 t/a. However, if the price of lithium carbonate is lower than US$4,800/t, then that is estimate to lower than 50,000 t/a.

6 Conclusions

6.1 Lithium reserves and resources abundant across the world

As one of the most important minerals for emerging industries, lithium will assume an increasingly important role in the economic development. However, the lithium consumption is relatively low. According to the minimum statistics provided by USGS, global lithium reserves could last 360 years; and the statistics from SNL MEG suggests that it could last over 640 years. Thus the lithium supply will be able to meet the global demand for a long term.

6.2 The supply of global lithium highly concentrated

The lithium production is unbalanced and concentrated. Geographically speaking, more than 70 % of lithium production is in Chile, Argentina, Australia and China. Meanwhile, more than 80 % of lithium suppliers are from SQM, Talison (51 % of Talison's share is held by Sichuan Tianqi Lithium Industries), Rockwood and FMC. Over 90 % of the saline lake lithium is provided by SQM, Rockwood and FMC. It can be concluded that the supply of lithium is in monopoly. In the coming ten years, the global lithium supply may exceed the demand for lithium as the lithium production capacity is 1.5 fold of the demand for lithium.

6.3 The demand for global lithium strongly in future

Global lithium demand will grow at an annual rate of 10% in the next ten years. Currently, the top four lithium-demanding markets are battery, glass, ceramics and lubricating greases. Battery industry, currently the biggest lithium-demanding market, will experience the fastest growth, with an annual growth rate of over 10 %. Following the battery industry is lubricating greases industry, with an annual growth rate of 3.5 %. Glass and ceramics industry will have an annual growth rate of 3 % to 5 %. The increasing demand for new energy vehicles, grid storage applications, electronics and electric tools gives a boost to the demand for lithium. It is estimated that the demand for lithium in China will reach 104,800 tons (LCE) in 2017. By the year of 2020 and 2025, China's lithium demand will be 131,800 tons (LCE) and 187,700 tons (LCE), respectively.

6.4 The potential of China's lithium resources

China, with around 3,500,000 tons of lithium resources, ranks the third. It is estimated that there are more than 10,000,000 tons of lithium brines resources in Tibet, Qinghai, and Xinjiang. One of the biggest difficulties facing the development of lithium brines is the high proportion of Mg/Li, which makes it less economically feasible to extract lithium from the saline lakes.

6.5 Outlook

Despite the rich lithium resources China has, the lithium supply cannot meet its demand for lithium in short term due to the lack of technology. Thus China will remain a lithium importer in a few years. The total lithium export from Chile, Argentina, Australia and United States reaches is over 150,000 tons, creating an abundant global lithium supply market that allows China to acquire sufficient lithium from international market, without causing others countries acquiring insufficient lithium from the global market.

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Supply and Demand of Gallium

Dieter Huy, Maren Liedtke

8 Introduction

Gallium (chemical symbol Ga, atomic number 31) is a blue-gray to silvery-white metal with orthorhombic crystalline structure. It was discovered in 1875 by the French chemist Paul Émile Lecoq de Boisbaudran. It ranks third in the boron group (group 13 according to IUPAC[1]). Besides mercury, caesium and rubidium, gallium is one of the few elements with a melting point near room temperature (29.78 °C). The metal remains in a melted state up to 2,204 °C, giving it the largest liquid range of all metal elements. Like water, gallium expands during solidification. The density of gallium in solid phase is 5.91 g/cm³ and in liquid phase 6.1 g/cm³. For further properties see table 17.

Table 17: Properties of gallium

Atomic number	31
Atomic weight	69.723
Boiling point	2.204°C
Density	5.91 g/cm³ near r.t / 6.095 g/cm³ when liquid
Hardness (Mohs scale)	1.5
Isotopes	^{69}Ga (60.11 %), ^{71}Ga (39.89 %)
Electron configuration	[Ar] $3d^{10}$ $4s^2$ $4p^1$
Oxidation states	3, 2, 1, -2, -4
Electronegativity (Pauling scale)	1.81
Thermal conductivity	40.6 (W/m)/K

9 Uses

The use of gallium compound based group III/V semiconductors has made gallium a high-tech metal in the past decades. The two main application fields are integrated circuits (ICs) and optoelectronic devices. The most common compounds are **gallium arsenide** (GaAs) and **gallium nitride** (GaN), in much smaller amounts **gallium antimonide** (GaSb) and **gallium phosphide** (GaP), representing about 94 % of current consumption (Roskill 2014).

Currently, the greatest use of gallium is in **GaAs**. GaAs is used as a substrate material (wafer) for the epitaxial growth of III/V semiconductors including indium gallium arsenide, aluminum gallium arsenide and others, as well as for the production of high-efficiency (> 20 %) copper-indium-gallium-selenium thin-film solar cells (CIGS). The largest use is in GaAs compound semiconductors in optoelectronic and microelectronic industries including integrated circuits (ICs) used in cell phones, infrared emitting diodes (IREDs), laser diodes (LDs), laser emitting diodes (LEDs), wireless communications, and high-end military applications.

The predominant use of **GaN** is in optoelectronics. It can be used to emit brilliant light in the form of light emitting diodes (LEDs) and laser diodes (LDs). It is also used in electronic devices for next generation high frequency, high power transistors capable of operating at high temperatures. **GaP** is used – standalone or compounded with other gallium components – in the manufacture of LEDs of different colours and in electronic devices like power amplifiers for WiFi and WiMAX applications. **GaSb** is used for infrared detectors, infrared LEDs and thermophotovoltaic systems.

Secondarily, gallium is used in neodymium-iron-boron magnets and batteries, high temperature thermometers, and in low melting alloys. An eutectic alloy of gallium, indium and tin (“Galinstan”) replaces mer-

1) *International Union of Pure and Applied Chemistry*

cury in fever thermometers. Gallium oxide is used as a constituent in plasma and fiber optic applications. Gallium citrate is used in medical imaging for cancer diagnostics (“gallium imaging”).

10 Occurrence and resources

Gallium is present in the Earth’s crust at about 18 ppm (Gao et al. 1998). It is not found in its elemental form and does not form economically recoverable concentrations. It mainly occurs as a trace element in aluminium, zinc and germanium minerals like bauxite, sphalerite and germanite, and in hard coal.

At present, gallium is only produced as by-product of the refining process of other metals during alumina production from bauxite or during zinc residue processing. The most important primary source for gallium is bauxite. Gallium can be also found in the fly ash produced by the coal and phosphates industries.

The United States Geological Survey (USGS) reports bauxite reserves of 28 bn t and zinc reserves of 230 Mt (USGS 2014). The leading countries are Guinea, Australia, Brazil, Vietnam and Jamaica for bauxite, Australia, China, Peru, Mexico, India, Kazakhstan and the USA for zinc (Figure 12).

Based on an average gallium content of 50 ppm (Jaskula 2014) and a recovery rate of 40 % (Elsner et al. 2010) contained gallium in bauxite amounts to 560,000 t. The gallium content of zinc ores ranges between 10 to 320 ppm (Butcher & Brown 2014). This some additional hundred tons could be contained in the world zinc resources. The current primary production of gallium is about 300 to 400 t/a (Roskill 2014), so primary gallium supply is secured for many hundreds of years (Figure 13).

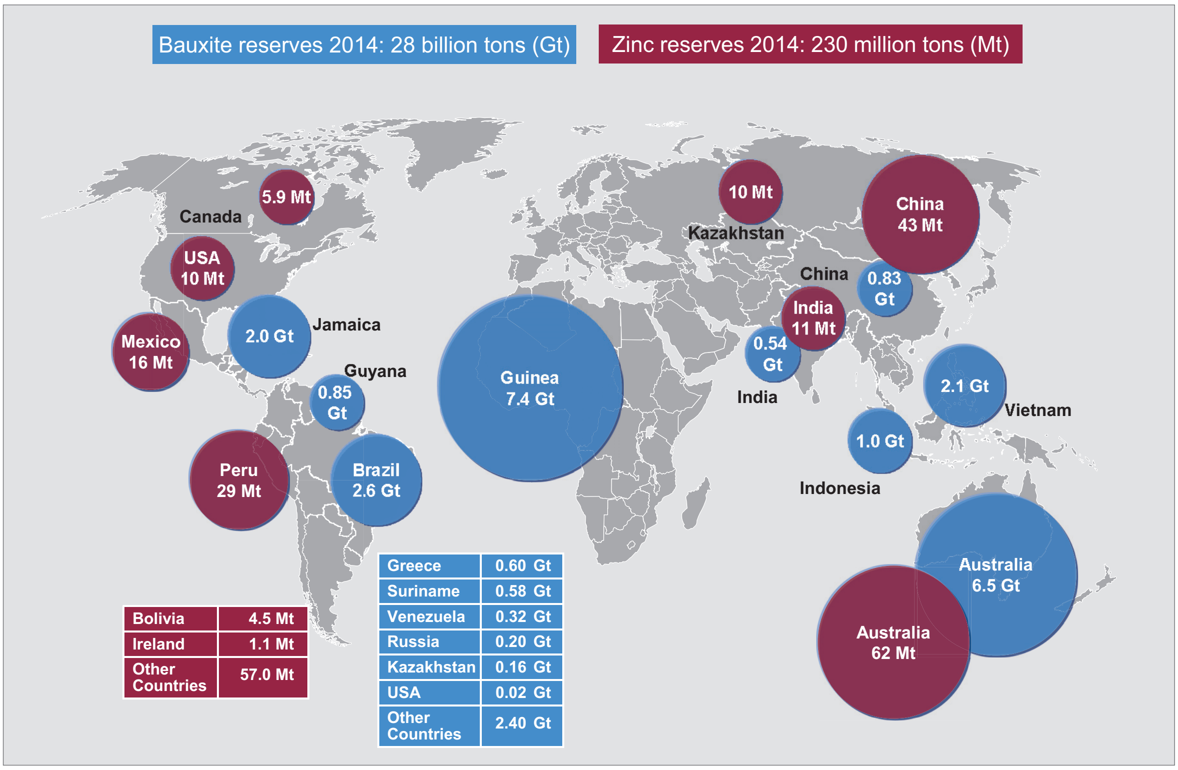

Figure 12: World distribution of bauxite and zinc reserves (data: USGS)

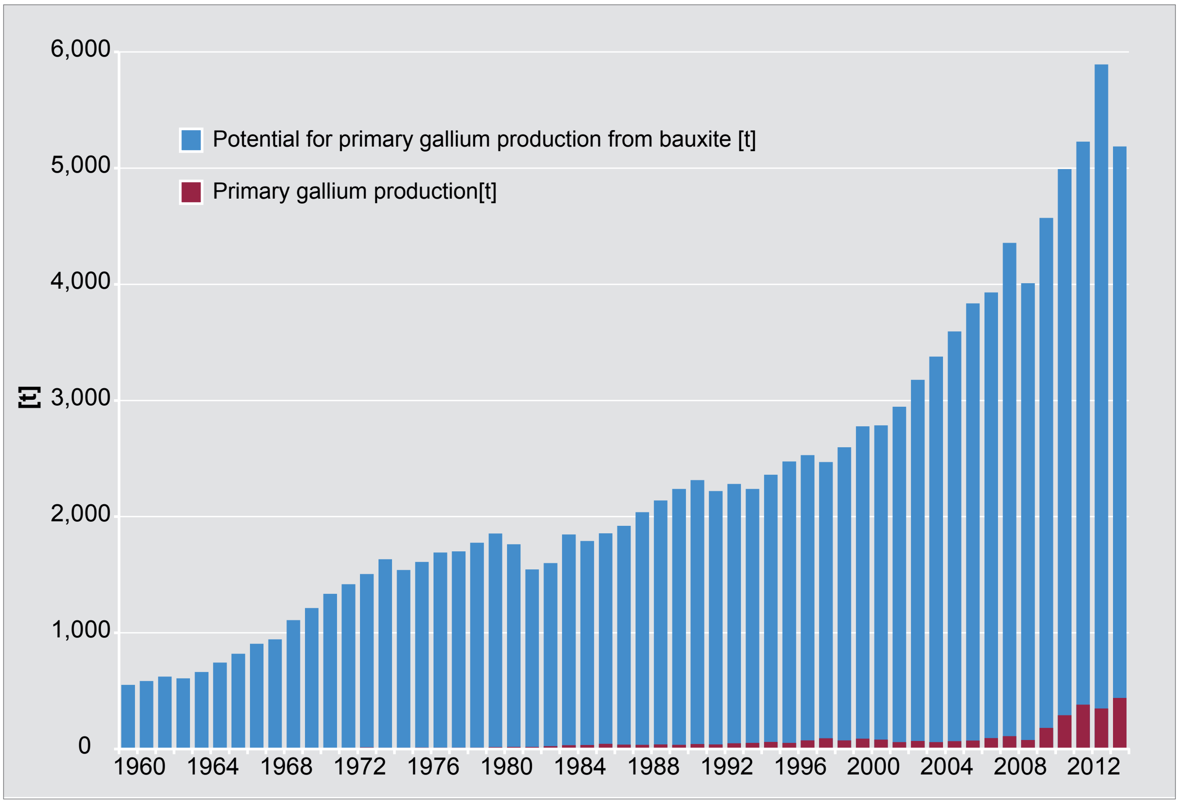

Figure 13: Potential for primary gallium production from bauxite

Globally, there are only a few deposits with gallium concentrations in the ore that are high enough to consider a recovery of gallium as main element. The most popular example is the Apex mine in Utah, USA, where St. George Mining Company brought into production the world's first mine with gallium and germanium as main elements in 1985 (Bautista 2003). The Apex Mine Mill processed dump and underground mined ore at 0.03 to 0.045 % gallium for only a few months. In 1987 the company went into liquidation as the gallium production did not prove to be economic. Currently there are no mines working primarily for gallium.

11 Production

Gallium is recovered both as primary production, and secondary from recycled gallium-bearing scrap, mainly compounds. Primary gallium is typically recovered at 99.9 to 99.99 % (3N, 4N), and then refined to higher purities depending on the further use. 4N gallium is used for metallurgical, chemical and solar applications. For electronic and compound semiconductor applications 6N (99.9999 %) to 7N (99.99999 %) purity is required. Very high purity gallium (8N) is used for molecular beam epitaxy (MBE) applications.

11.1 Primary production

About 90 % of current primary gallium production is extracted from bauxite during the refining of alumina. The most commonly used process for the production of alumina from bauxite, and thus gallium is the Bayer process, named after the Austrian chemist Karl Joseph Bayer, who developed a method for supplying alumina to the textile industry in 1888 (Seecharran 2010). During the process the aluminium bearing minerals in bauxite – gibbsite, boehmite and diaspore – are selectively extracted from the insoluble components by dissolving them in a solution of sodium hydroxide (caustic soda) at high temperatures and high pressure. The solution contains sodium aluminate and non-dissolved bauxite residue containing iron, silicon, titanium, aluminium, and other elements in small quantities, including gallium.

There are various options to recover gallium from sodium aluminate solutions such as fractional precipitation, electrochemical deposition, solvent extraction, and ion exchange. Solvent extraction is an efficient method. By using the Kelex 100 system, about 80 % of the gallium in Bayer liquor can be extracted. However, the kinetics of the extraction process has been proved to be very slow, generally requiring several hours. Ion exchange is the main method applied in industry for gallium recovery from Bayer liquor. Duolite ES-346 and DHG586 exhibit good extracting properties for gallium, and are used as industrial resins (Zhao et al. 2012).

A small amount of gallium is produced as by-product of zinc extraction from sphalerite ore (ZnS). During this process the sphalerite is first roasted to zinc oxide (ZnO) and then leached with sulphuric acid. Gallium is contained in impurities which are separated from the leach solution. Using Duolite ES 467 or HDP ion exchange resins the gallium is recovered from these residues by ion exchange (Jacquin et al. 1987).

Finally, during production of alumina as well as during refining of zinc, electrowinning is used to create a crude gallium metal at purities of 99.9 to 99.99 % (3N/4N gallium) (Figure 14).

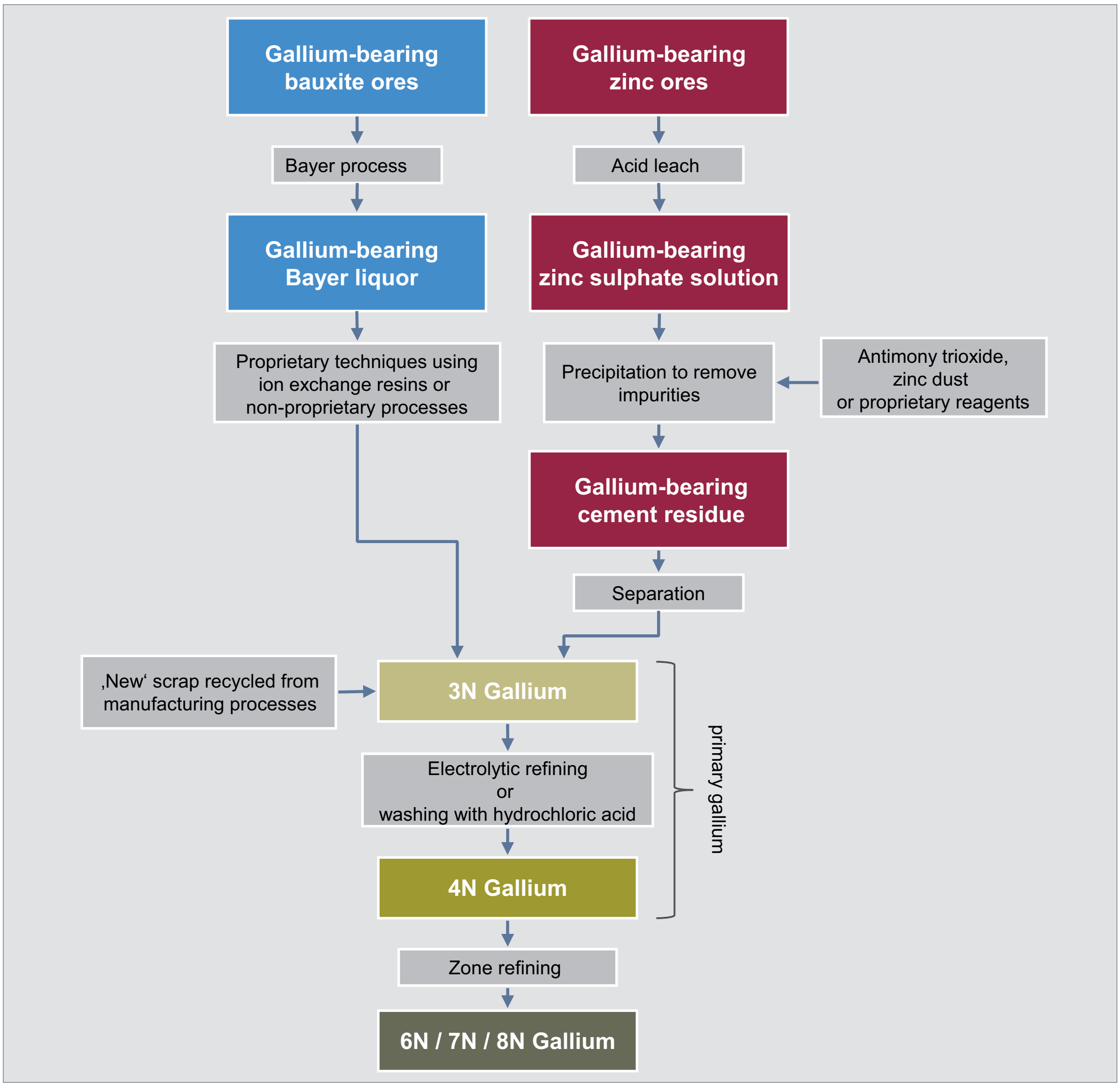

Figure 14: Processes of extracting gallium from bauxite or zinc ores (after Butcher & Brown 2014)

World primary production

The USGS estimates the world primary gallium production to be 440 t in 2014, a plus of 26 % compared to the previous year before (350 t). China, Germany, and the Ukraine were the leading producers. Lesser output came from Japan, South Korea, and Russia (Jaskula 2015a).

From the beginning of the 1970th to the end of the 1990th production of primary gallium rose continuously at a compound annual growth rate (CAGR) of 7.3 %. Between 2001 and 2004 production fell owing to lower demand for gallium in the electronics industry. Since 2005 production is rising sharply with growth rates of nearly 20 %, only briefly interrupted by the financial crisis in 2009 (Figure 15). Overall, the CAGR from the beginning of the 1970th to 2014 is 8.4 %.

World primary production capacity

Global estimated capacities for the production of crude gallium amounted to 680 t (Jaskula 2015a). China has available capacities of about 550 t. Outside China the production capacities add up to about 123 t (Jaskula 2014b; Naumov 2014): Germany accounting for 40 t, followed by Kazakhstan (22 t), South Korea (16 t), Ukraine (15 t), Russia (12), Japan (10 t), and Hungary (8 t). In the past, further production capacities were indicated for Australia, the USA, and Slovakia. Between 1994 and 2014 global capacity has been increasing by 8 % annually. Since the end of the 1990s, especially China has ramped up production capacities massively and is currently disposing of more than 80 % of the global crude gallium capacities.

During the past years, the production was usually below 50 % of the capacities, rarely above. Merely during the short period of 2010 to 2012 there was an increase in capacity utilization between 70 and 80 % (Figure 15).

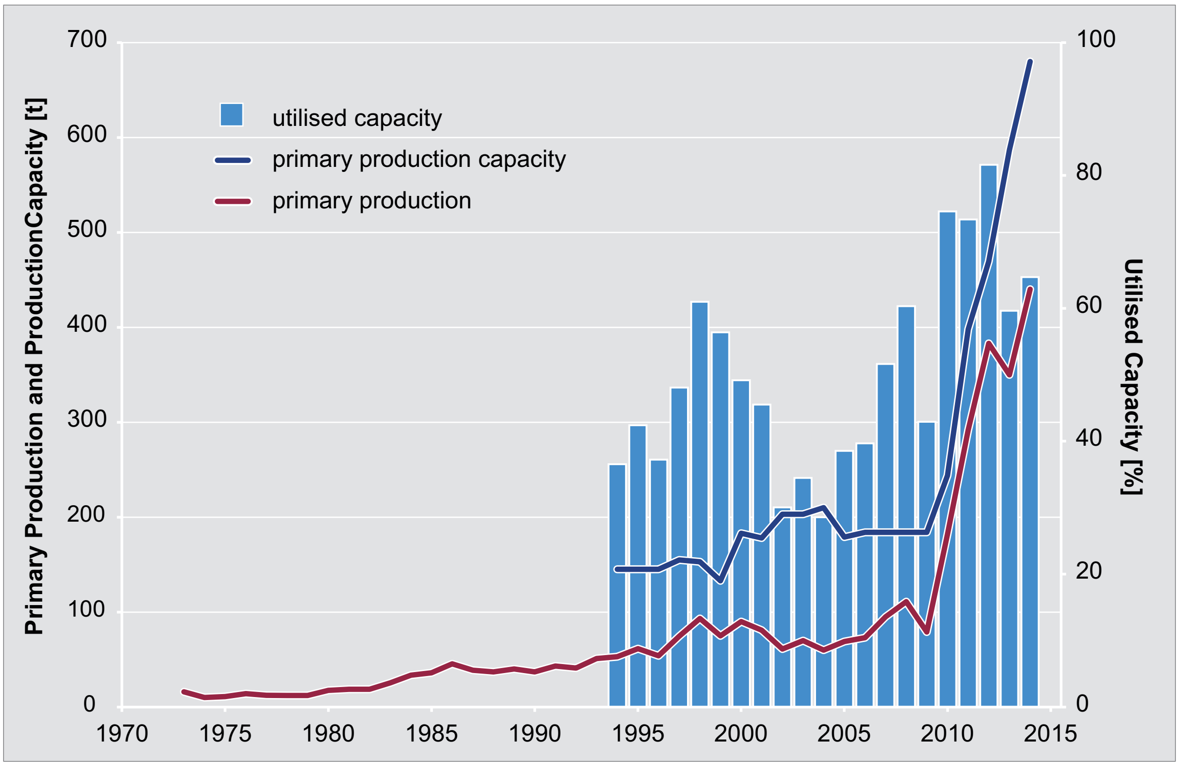

Figure 15: Production, production capacity and capacity utilization of primary gallium

11.2 Secondary production

Recycling of gallium is another significant source for the market. At present, no gallium is recovered from post-consumers scrap, so the wastes from the production of GaAs and GaN wafers are the most important source for secondary gallium. The fabrication of these semiconductor wafers generates about 60 % new scrap, with a gallium content ranging from 1 to 99.99 % (Butcher & Brown 2014).

Worldwide secondary capacities are estimated at 200 t.

11.3 Refinery production

Gallium at 3N/4N purities (99.9 to 99.99 %) obtained from primary and secondary production must be refined to higher purities, typically by fractional crystallization and zone refining up to 7N/8N dependent on the further use.

Reliable data for production and capacity of refined gallium are very difficult to obtain and in many cases, it is impossible to differentiate wether production is derivet from secondary gallium or upgraded 3N/4N gallium.

According to estimates of the USGS refined gallium production in 2014 was about 170 t, 15 % less than 2013. Refinery capacity was 230 t in 2014. Only 39 % of the primary gallium production of 440 t was refined, compared to 70 % in the year before.

Principal producers of refined gallium from primary material were China, Japan, the United Kingdom, the United States, and Canada. Principal producers of refined gallium from secondary material were Japan, China, the United Kingdom, the United States, Slovakia, and Germany.

12 Gallium producers by country

Australia

Currently there is no gallium production in Australia. In the first half of the 1990s, Australia was a major producer of primary gallium from Rhône-Poulenc’s 50 t/a facility which was established in 1989 near Alcoa’s Pinjarra alumina refinery. The plant produced gallium chloride which was exported to France, where Rhône-Poulenc refined gallium at its Salindres plant. Oversupply of gallium resulted in the shut-down of several gallium recovery facilities worldwide, including Pinjarra which was mothballed after only one year in operation. Rhône-Poulenc stated, that it had sufficient gallium stockpiled at the plant to meet current demand levels and would not reopen the plant until market conditions improved (Kramer 1992). In 1998, Rhodia Chimie S.A. founded following the spin-off of the chemicals, fibres and polymers activities of Rhône-Poulenc, took over the gallium business and operated Pinjarra by its Australian subsidiary Rhodia Pinjarra Pty Ltd. In 1999 the US company GEO speciality chemicals acquired Rhodia. GEO Gallium S.A. a subsidiary of GEO speciality chemicals announced to double the capacity of Pinjarra to 100 t/a in 2002 (CS 2001) but the plan was never realized.

Canada

Although Canada is one of the top five producers of zinc there is no production of primary gallium.

Molycorp Minerals Canada ULC is the Canada division of **Molycorp Inc.** (see section USA). Molycorp Canada recovers gallium and indium from low grade manufacturers waste and residue at its Peterborough, Ontario hydrometallurgical plant. The plant was owned by Recapture Metals Ltd. and acquired by Toronto-based Neo Material Technologies Inc. in 2009 (SemiconductorToday 2009). Neo Material itself was acquired by Molycorp in 2012 (Molycorp 2012). Molycorp (2015b) reports a gallium production from scrap feedstock of 13 t for 2013 and 2014 respectively; this includes gallium production at Molycorps US plant at Blanding, Utah. Roskill (2014) reports an upgrading capacity of 30 t/a at Peterborough.

China

China is by far the major producer of both, primary and refined gallium. The primary gallium production capacity of China is estimated at 450 – 470 t for 2013 (Jaskula 2015b, Roskill 2014) and 550 t for 2014 (Jaskula 2015a). Most of the gallium is produced as a by-product from Bayer liquor during alumina production, only small amounts originated from zinc production. According to Roskill (2014), China has capacities of at least 170 t for upgrading and recycling of gallium. In 2013 China produced 327 t of gallium (Information Center of Ministry of Land and Resources (ICMLR), personal communication, October 22, 2014). The Fanya Metal Exange reported stocks of 197.46 t in August, 2015, and nearly reached its total storage capacity of 200 t for gallium (Fanya Exchange 2015), in addition to at least 50 t at the State Reserve Bureau of China (SRB) (MetalBulletin 2013).

Major Chinese producers of primary gallium are

- **Zhuhai SEZ Fangyuan Inc**. is China's and the world's largest producer of primary gallium. It accounts with a capacity of 140 t per year at six locations for more than 30 % of total world output. The company produces 4N and 6N gallium and is owner of a patent of a chelating resign for adsorbing gallium ("GaXW-7", State invention patent no. ZL03112341) (Zhuhai Fanyuan 2015).
- **Aluminium Corporation of China Ltd.** (CHALCO) produces gallium metal and gallium oxide at four sites at Shandong, Henan, Guizhou and Shanxi province (CHALCO 2015a). In 2014 the company produced 81.2 t of gallium, after 127.8 t in 2013 and 39.2 t in 2012 (CHALCO 2015b).
- **East Hope Mianchi Gallium Industry** at Mianchi County, Henan Province ranks third with a capacity of 80 t/a and a production of 40 t/a (Roskill 2014).
- S**hanxi Jiahua Tianhe Electronic Materials** is a joint venture of Molycorp, Shanxi Aluminium Plant and Beijing JiYa Semiconductor Material. Its capacity is estimated at 50 t/a (Roskill 2014).
- **Xiaoyi Xingan Gallium Co.**, Ltd was founded 2011 by Xiaoyi Xingan Chemials Co. Ltd, a subsidiary of Hangzhou Jinjiang Group, one of the major alumina and aluminium producers in China. (50 t/a). The company reports a capacity for the production of 4N gallium of 50 t/a and has the world's largest single production line (Xingan 2015).
- **Beijing JiYa Semiconductor Material Co.** is a joint venture of the US company AXT Inc., Consco Group, Hong Kong and Shanxi Aluminum Plant and has a capacity of 45 t/a (Roskill 2014).
- **Shanxi Zhaofeng Gallium Industry Co.** is a joint venture of Shanxi Zhaofeng Aluminum Co., Ltd of Yangmei Group, Beijing JiYa Semiconductor Material Co., and Chalco Jinlv Refr Co. It has a capacity of 20 – 40 t/a (Roskill 2014).

Secondary and refined gallium is provided by

- **Nanjing Jinmei Gallium Co., Ltd.**, a joint venture between the US company AXT Inc. (83 %) and Nanjing Germanium Factory (17 %) (AXT 2015, CNGE 2015). On its website the company reports capacities for the production of 100 t of high-pure gallium of 5N to 8N, including MBE gallium, of 50 t for crude gallium from recycling, of 6 t for 4N/5N gallium oxide, and of 2 t for 4N/5N gallium nitride (NANJING 2015).
- **MCP Metals (Shenzen)**, owned by 5N Plus, Canada has upgrading capacities of 20 t/a (Roskill 2014). A joint venture called MCP Crystal was formed in 2009 between the MCP Group and the Chinese company Golden Harvest Ltd. to create an integrated gallium operation capable of producing both low-purity and high-purity gallium. The joint venture consisted of four operations, three 99.99 % (4N) plants and one 6N and 7N plant. The 4N plants were expected to collectively produce between 70 t/a and 80 t/a of gallium. The plants were located in Henan, Shangxi, and Sichuan Province (Jaskula 2011).
- **Vital Materials Co.** produces high purity gallium (5N – 7N). In 2013 Vital Materials entered into an agreement with Hangzhou Jinjiang Group to form a joint venture for the production of gallium. The joint venture operation will produce 60 t/a (Vital 2013). Crude gallium is supplied by Jinjiang's subsidiary Xingan Gallium. In addition to gallium metal, Vital produces gallium compounds like gallium oxide, chloride, sulfate, nitrate, phosphide, antimonide and trimethyl gallium and recycles gallium from gallium-bearing scrap.
- **Emei Semiconductor Material Factory & Institute** is according to its company profile the biggest producing center for high pure elements and compound materials in China (EMEI 2012). The company was founded in 1964 and is situated in Leshan, Sichuan province. The company produces and sells a wide range of high purity elements including gallium of 5N – 7N.
- **Sichuan Western Minmetals Co., Ltd.** is a supplier providing a wide range of high purity metals and oxides including gallium metal of 5N – >7N and gallium oxide and gallium trioxide of 4N – 5N. The company is headquartered at Chengdu, Sichuan province (SWM 2015).
- **Sumika Electronic Materials (Shanghai)** was established as a 70/30 joint venture named Shanghai Sumika High Purity Metal Ltd. in 2001 by Sumitomo Chemicals Co. Ltd and Inabata & Co., Ltd, Japan. The refining facility has a capacity of 40 t/a of 6N – 7N gallium metal, which will be supplied to Sumitomo (Kramer 2001)
- **Zhuzhou Keneng New Material Co., Ltd.** was established in 2001 at Zhuzhou, Henan privince. The main products include indium, bismuth, tellurium, and 4N and 6N gallium (ZZK 2015).

France

Currently there is no production of gallium in France. Until 2006 **GEO Gallium S.A.** a subsidiary of US Geo Speciality Metals Inc., was the leading producer of refined gallium at its Salindres plant (formerly owned by Rhône-Poulenc and Rhodia Chimie S.A.) using primary gallium produced at its Ingal Stade plant, Germany as feed material. After GEO Gallium had sold Ingal Stade to MCP, Great Britain and recapture Metals, USA, the Salindres facility was subsequently closed and at yearend Geo Speciality Metals Inc. no longer operated its Geo Gallium subsidiary (Kramer 2007).

Germany

Ingal Stade GmbH, based in Stade near Hamburg, is Germany's sole producer of primary gallium and the biggest outside China. The company is located on the premises of Aluminium Oxide Stade Gmbh (AOS), an alumina refinery with a current production in excess of 900,000 t/a of aluminium oxide (Al_2O_3), owned by Dadco Alumina & Chemicals Ltd. Ingal Stade was founded as International Gallium in 1989 and, meanwhile, has since changed ownership several times. Presently, Ingal Stade is a 50:50 joint venture between the Canadian 5N Plus and the US company Molycorp Inc.

Ingal extracts annually about 30 t of primary gallium from Bayer process liquor of the alumina refinery. For further treatment and refining up to 7N purity the gallium is shipped to the owners' facilities in the UK and the USA.

PPM Pure Metals GmbH at Langelsheim, Germany has a very long tradition in the production and refining of high purity metals and compounds. It started with a smelter for processing lead and zinc in 1575. Later it was an operation site of the German Preussag AG. Since 1988 PPM is part of the French Recylex S.A. PPM is engaged in the production of high purity minor metals and their compounds for mainly the electronic, opto-electronic, and photovoltaic industries. This includes ultra pure metals (up to 7N5 quality) and compounds of the elements antimony, arsenic, cadmium, copper, gallium, germanium, indium, lead, tellurium, and tin. PPM produces gallium from 4N – 8N purity by recycling scraps, residues and slurries from gallium arsenide pulling, wafer and epitaxial processing, and other gallium containing materials (PPM 2015). Roskill (2014) estimates a capacity of 10 t/a.

Hungary

Magyar Aluminium Zrt. (MAL) was established in 1995 when the Hungarian aluminium industry was privatized. In Ajka, situated about 150 km west of Budapest, MAL is operating an alumina facility processing domestic ores. Since the acquisition of the bauxite operation Rudnici Boksita Jajce in 2004 Bosnian ores have been shipped to Ajka, where Mal is extracting crude gallium from Bayer liquor with a purity of 4N to 7N (MAL 2014). There is an estimated capacity of 8 t per year. The last reported production was 3.9 t in 2009 (Roskill 2014). According to company reports gallium production stopped in 2013 (MAL, personal communication, June 24, 2014).

Japan

Japan has a production capacity of primary gallium of about 10 tons per year. It is recovered from the by-products of the zinc smelting process of **Akita Zinc Co., Ltd, Iijima Smelting Plant**, an 81 % subsidiary of **DOWA Metals and Mining Co., Ltd.** Akita refines zinc from imported ore mainly from DOWA's 39 % share Tizapa mine in Central Mexico (DOWA 2015a), as Japan has no domestic zinc ore production. The subsequent treatment to high-purity (7N) gallium is carried out by DOWA Electronics Co., Ltd.

Japan's gallium supply in 2013 was about 140 t of which 71.5 t were sourced from recycled scrap (Jaskula 2015b). About 60 t of gallium are imports, the remainder is primary gallium from zinc refining. According to Roskill (2014) Japan has capacities of about 210 t for upgrading and recycling of gallium. There are five companies reporting refining, upgrading or recycling of the metal (RLJ 2007):

- **Dowa Electronic Materials Co., Ltd** refines gallium that is produced from by-products of the zinc smelting process at Akita Zinc Co's Iijima Smelting Plant and from recycled gallium scrap to purities up to 7N (DOWA 2015b). Capacity is estimated at 90 t/a (Roskill 2014). By its own account the company holds the no. 1 share in sales of high purity gallium in the world market. Dowa Electronics also supplies gallium oxide, gallium arsenide and gallium nitride based epitaxial wafers and LEDs.
- **Sumitomo Chemicals Co.** is a major Japanese chemical company and a member of the Sumitomo Group. The company has high purity gallium capacities of about 100 t/a of which 60 t are at Ehime plant, Japan, and 40 t provided by Sumika Electronic Materials (Shanghai) (ICIS 2001). Sumitomo Chemicals Co. is thus one of the world's largest producer of the metal. Sumitomo Chemical's gallium products include high purity gallium, trimethy gallium, triethyl gallium, and gallium arsenide wafers. In April, 2015 Sumitomo Chemicals acquired Hitachi Metals, Ltd's compound semiconductor materials business.
- **Rasa Industries, Ltd.** started as Rasa Island Phosphate Ore Co., Ltd. in 1911. The production of high purity gallium from semiconductor wafer scrap began 1982 at Osaka factory. Rasa's Electronic

Materials Sector is engaged in the manufacturing and sale of high purity inorganic materials, including gallium of 6N/7N purity (RASA 2015). Roskill (2014) estimates upgrading and refining capacities of 35 t/a.

- **Nippon Rare Metal, INC. (NRM)** started in 1958 as a supplier of selenium, photoelectric cells and metal salts. In 2000, the company began with the recovery of gallium and tantalum (NRM 2015). It produces 4N – 5N gallium and gallium oxide from wafer production scrap and copper-indium-gallium-selenium (ICGS) scrap from thinfilm solar sector. Roskill (2014) estimates upgrading and refining capacities of 10 t/a.
- The **Nichia Corporation**, headquartered in Tokushima is one of the world's largest producer of gallium compound based LEDs with distribution offices around the world (NICHIA 2015). Roskill (2014) estimates upgrading and refining capacities of high purity gallium of at least 15 t/a.

Kazakhstan

Kazakhstan has an annual production capacity of crude gallium of 20 – 22 t. Aluminium of Kazakhstan (AoK), a subsidiary of the internationally operating mining company **Eurasian Natural Resources Corporation PLC (ENRC)**, is extracting about 5 Mio. t of bauxite per year in the region of Pavlodar in the northeast of Kazakhstan. Production of alumina amounts to 1.5 Mio. t. In the process gallium is recovered as a by-product. From 2008 to 2011 there was an annual primary gallium output of about 18.7 t. In 2012, the production decreased to 15.7 t (ENRC 2014), and since 2013 ENRC has stopped the production of gallium completely.

Russia

The primary gallium production capacities of Russia are estimated at 12 t/a. OAO **Pikalevskii glinozem (Pikalevo Alumina)** which operates as a subsidiary of LLC BaselCement produces gallium from apatite nepheline ore. **OOO Gallii (Gallium)** at Kamensk-Ural produced gallium from bauxites. The company has a capacity of 4 t/a but stopped production in 2012 (Naumov 2014).

Slovakia

Until 2009 the USGS reported capacities for the production of primary gallium of about 8 t/a for Slovakia (Jaskula 2011), but since 2010 there is no production of primary gallium in Slovakia.

CMK, s.r.o. based in Zarnovica was founded in the 1970's as a research institution in the field of gallium and gallium arsenide processing. The company's portfolio covers gallium arsenide wafers and gallium metal of 4N, 6N, and 7N purity. The gallium is refined from low purity primary gallium (3N, 4N) and from recycled waste material containing gallium (gallium arsenide, chloride, oxide).

Current capacity and production data are not available, the last reported data where recycling and refining capacities of 25 t/a for the years 2006 – 2009 and a production between 16.75 t (2006) and 6.05 t (2009) (Roskill 2014).

South Korea

Korea Zinc Co., Ltd. began producing 6N primary gallium as a by-product of its zinc smelting operation at Onsan in the first quarter of 2010 with an estimated annual capacity of 10 t. After several facility expansions between 2010 and 2012 the current capacity is estimated to be between 16 and 20 t/a (Korea Investment 2012, Roskill 2014).

Ukraine

The Ukraine has estimated primary gallium production capacities of about 15 t/a. The gallium at purities of 99.99 % and 99.999 % is produced at the Nikolaev Alumina refinery owned by **United Company RUSAL Plc (RUSAL)**, which refines bauxite imported from Guyana and Guinea. The refinery has an annual production capacity of 1.6 Mio. t of alumina. According to company information, the Nikolaev refinery is currently carrying out a program to boost the output of both alumina and gallium (RUSAL 2014).

United Kingdom

There is no primary gallium production in the UK.

5N PLUS UK Ltd. recovers and refines gallium from imported primary gallium metal and new scrap at the former Mining & Chemical Products' (MCP) Wellingborough plant. MCP, part of the Belgian based MCP Group SA, was acquired by the Canadian 5N PLUS Inc. in 2011. 5N PLUS is specialized in the production of minor metals including gallium. The Wellingborough plant is supplied primarily by Ingal Stade, Germany, where 5N PLUS has a 50 % interest as part of the MCP acquisition. MCP refines gallium of 7N including gallium tri-chloride and gallium oxide. Capacity is about 20 t/a (Roskill 2014).

USA

No primary gallium has been recovered in the USA since 1987 (Jaskula 2015a). There is only one company which recovers and refines gallium from imported primary gallium metal and new scrap:

Molycorp Inc. is an American mining corporation headquartered in Greenwood Village, Colorado, USA. It is one of the world's leading manufacturers of rare earth and rare metal products with 25 locations across ten countries (Molycorp 2015a). Molycorp produces high purity gallium in 4N, 6N, 7N and MBE (8N) grades from high purity gallium arsenide scrap as well as by upgrading primary gallium from various global producers.

Molycorp Blanding: Refining of gallium, both from scrap and from primary gallium takes place at its Blanding plant in Utah. In 2013 and 2014, Molycorp produced 46 t and 57 t respectivetly of refined gallium from primary metal, and futher 13 t annually from scrap feedstock (the last includes production at its Peterborough, Canada plant; see Canada section).

In the years 2012 and 2013, primary gallium was supplied primarily by Ingal Stade, Germany, where Molycorp acquired a 50 % interest as part of the Molycorp Canada acquisition. In 2013 and the precding second half of 2012, Molycorp purchased gallium from Ingal Stade for approximately 4.9 million US$ and 3.3 million US$, respectively (Molycorp 2015c). In December 2014, however Molycorp decided to cease purchasing gallium metal from Ingal Stade "… because the joint venture can no longer provide this metal at a competitive price …" (Molycorp 2015b). In addition Molycorp manufactures gallium nitrate and gallium oxide at the Blanding plant.

Molycorp Rare Metals Oklahoma: By taking over Neo Material in 2009 (see Canada section) Molycorp acquired an 80 % interest in the Quapaw facility in Oklahoma, formerly known as Gallium Compounds. Quapaw is recognized as a leading manufacturer of gallium tri-chloride.

13 Demand

Global gallium consumption is estimated at 285 t in 2014 (RLJ 2014), a rise of merely 1 % compared to the year before, but an increase of more than 70 % compared to 2009 (Figure 16).

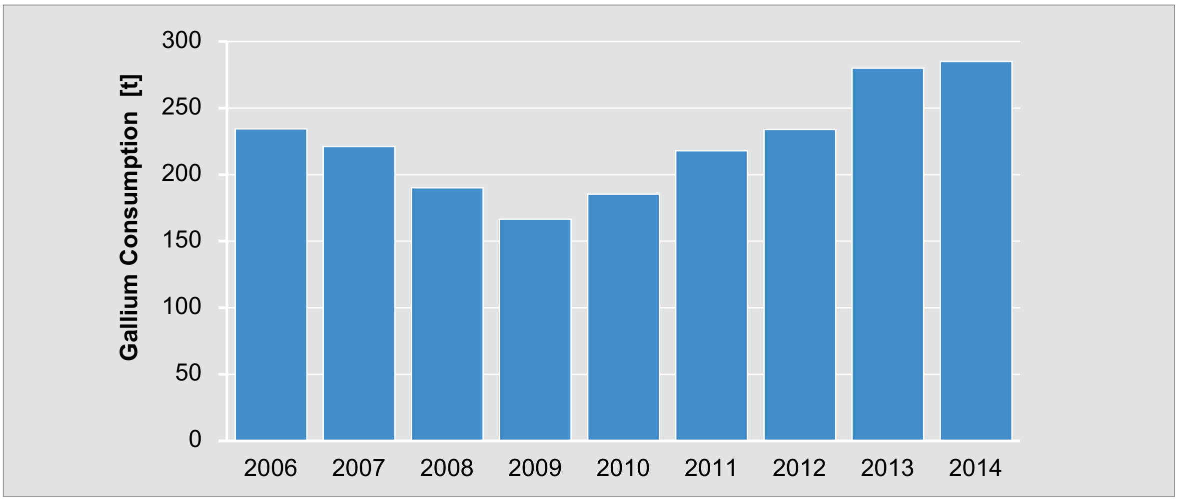

Figure 16: Worldwide gallium consumption

The largest market for gallium is still in Japan, which consumed 97 t in 2013 (Jaskula 2015b). Its share of the global market has fallen from about 80 % in the mid 2000s (Roskill 2014) to about 35 % in 2013, while China's demand grew rapidly to 67.5 t in 2013 (ICMLR, personal communication, October 22, 2014), a share of 24 % of the global market. The USA ranks third with 37.8 t (13.5 %), similar to the European market which is estimated at 30 – 40 t.

About 90 % of the global gallium demand is used in semi-conducting or semi-insulating (SC/SI) substrates and epitaxial layers of which 50 % accounted for integrated circuits (IC) and discrete field effect transistors (FETs) and 38 % LEDs for general lighting and backlighting; 2 % are other SC/SI applications. The remaining 10 % are photovoltaics (CIGS) (4 %), magnets (3 %) and other minor applications (3 %) (Roskill 2014; Figure 17).

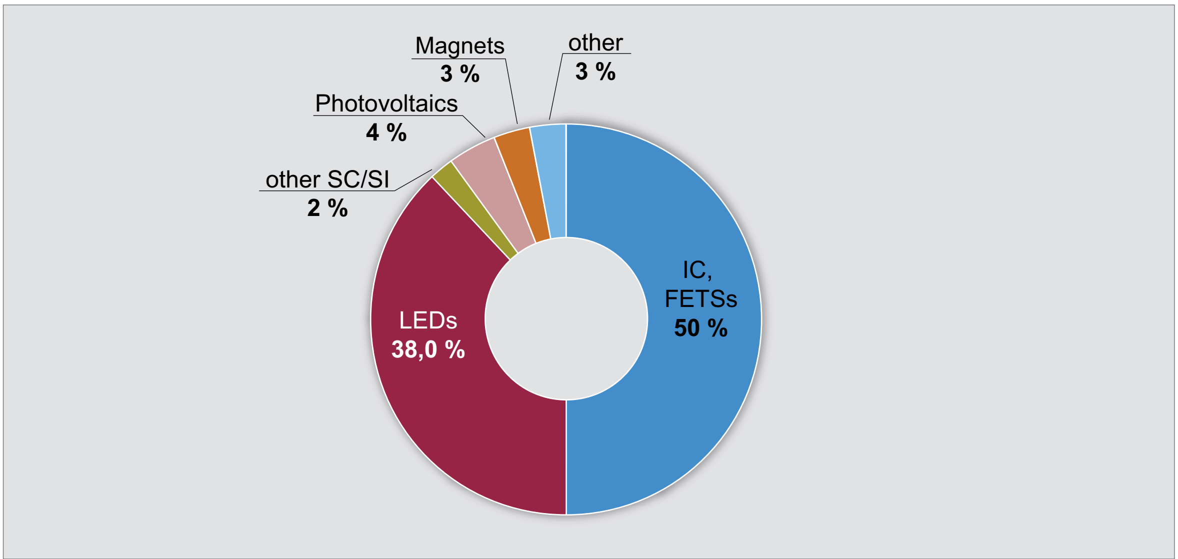

Figure 17: Worldwide gallium consumption by application (source Roskill 2014)

There are no up-to-date data for **Japan's** gallium consumption by end use. Latest data provided by Dowa in 2009 estimated 49 % for GaAs and GaP substrates, 46 % for epitaxial layers for the production of LEDs. The remainder includes other, mainly GaN-based applications, which according to estimates of (Roskill 2014) has increased to about 20 % in 2013. Presently, Japan is by far the largest producer of GaN wafers, accounting for about 85 % of worldwide production (Jaskula 2015b).

According to data sourced by the Fanya Metal Exchange, Roskill (2014) estimated **China's** consumption of gallium at 61 % for GaAs substrates and epitaxial layers for FETs, MIMICs and LED production, 24 % for LED coating mainly by GaN epitaxial applications, 6 % for the production of the production of high strength neodymium-iron-boron magnets, 4 % for solar energy applications, and 5 % for other minor applications.

In 2013, 74 % of the gallium consumption of the **United States** accounted for the production of ICs, 25 % to manufacture optoelectronic devices such as laser diodes, LEDs, photodetectors, and solar cells; 1 % accounted for research and development (Jaskula 2015b; Figure 18). Compared to 2012, gallium consumption for use in ICs increased by 21 % owing to an increased demand for third- and fourth-generation smartphones, which use up to 10 times more GaAs than standard cellular phones, and by an increasing demand for military applications. Owing to increased installation of CIGS solar cells, gallium demand from the solar cell and photodetector industry increased by 44 %. Gallium consumed for the production of laser diodes and LEDs decreased by 19 % owing to China's rapidly growing LED industry.

There are only few data concerning the market for gallium in **Europe**. We estimate the consumption of gallium at about 30 – 40 t/a. Major manufacturers of gallium compound substrates and wafers, and solar cells are located in France, Germany, the Netherlands, Poland, Slovakia, and the UK (Roskill 2014). In Germany, the Freiberger Compound Materials GmbH (FCM) is the biggest producer of GaAs wafers in Europe with a worldwide share of 50 – 60 % for the production of 6" wafers (FCM, personal communication, March, 13, 2015).

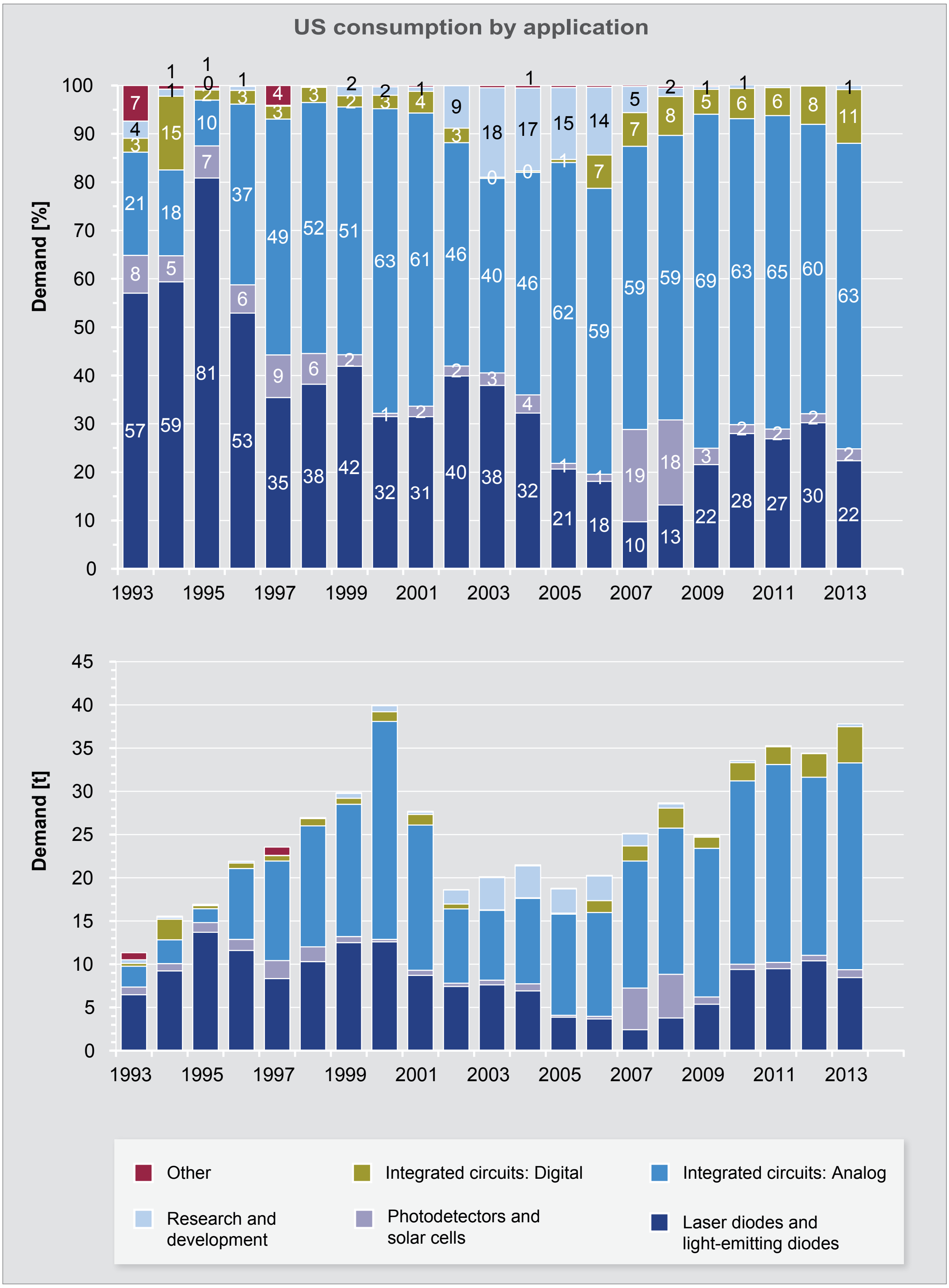

Fig. 18: US consumption of contained gallium by end use (after JASKULA 2015b)

14 Prices

Gallium is not traded at the stock exchange. Prices are negotiated bilateral usually on a long term base between suppliers and customers. Between 1960 and 2013 prices for 6N gallium in the American metal market fell on a compound annual growth rate (CAGR) of – 3.1 %. The biggest drop in prices of more than 10 % occurred in the 1960s owing to improved commercial methods of metal extraction and an unchanged demand. Since the 1980s gallium prices have been relatively stable in a range between 400 and 600 US$ on a CAGR of – 0.7 %, only occasionally interrupted by smaller peaks, i.e. in 2001 when rumors of supply shortages owing to rising demand for gallium arsenide for new-generation mobile phones were spread (Figure 19).

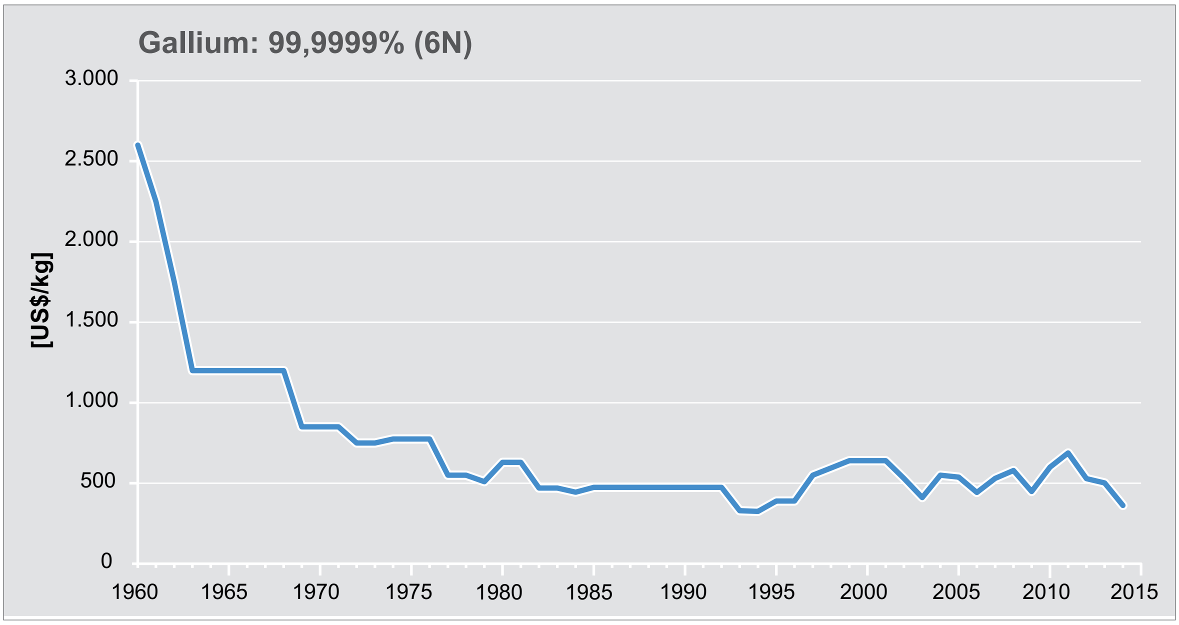

Figure 19: 6N Gallium prices, January 1960 to 2014

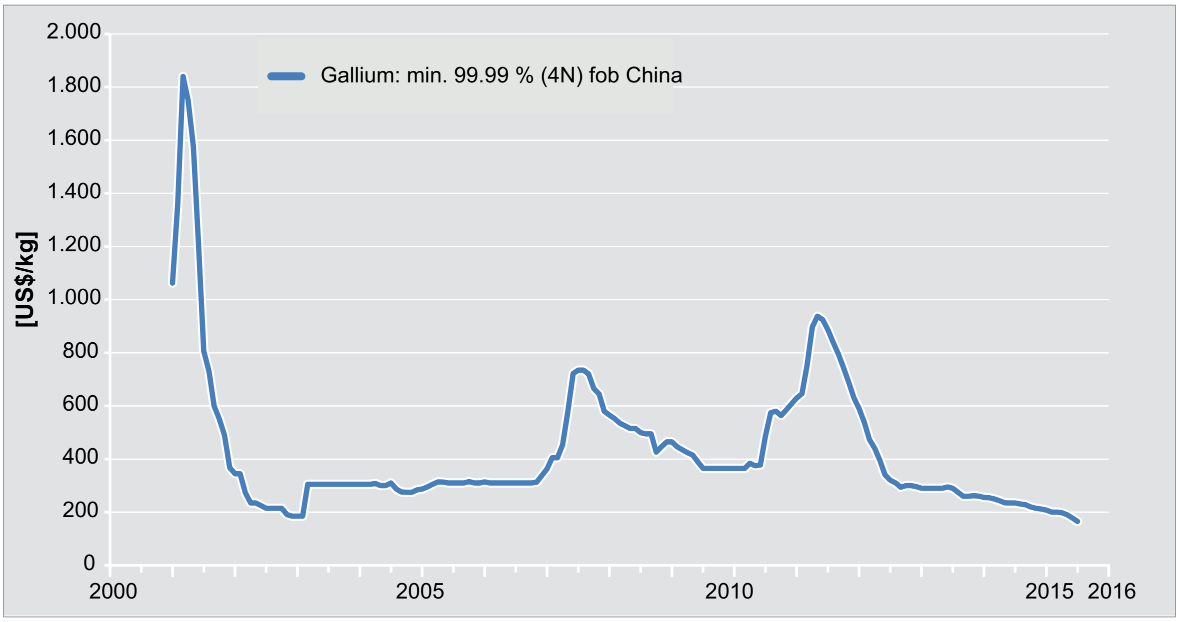

Figure 20: 4N Gallium prices, January 2001 to July 2015

Prices for unwrought gallium (99.99 %, fob China) peaked at 1,840 US$/kg in April, 2001 for the same reasons. By January 2002 the price had dropped to 368 US$/kg, followed by a long period of a price range between 300 and 400 US$/kg until March 2007. During the second and third quarter 2007 the prices increased up to 735 US$/kg, which was attributed to the introduction of export licenses for Chinese gallium exports, higher demand for gallium in gallium arsenide compound semiconductors for cellular phones, and for AlInGaP and gallium phosphide compound semiconductors in LEDs (RLJ 2007). Lower demand during the worldwide financial crisis lead to decreasing prices to levels before 2007. In 2011 prices rose again up to nearly 940 US$/kg owing to expectations of a significant increase in demand in CIGS photovoltaic cells and gallium nitride white LED (RLJ 2012) and tightness of supply as end users restocked inventories after the financial crisis (Jaskula 2011). Prices decreased again to the former level at about 400 US$/kg within one year when newly primary gallium capacities in China reached the market. By July 2015, prices continued to fall steadily to 165 US$/kg as demand remained weak (Figure 20). This is a decrease of nearly 80 % compared to the annual average of the year 2011. Between 2002 and the first half of 2015 prices for primary gallium decreased at a CAGR of -0.74 %.

15 Trade

Data on the global trade of gallium are difficult to obtain, as they are often incomplete and partially contradictorily. International trade code systems like the “Harmonized System” (HS) merged gallium with other elements (i.e. HS Code 811292 “Unwrought gallium, hafnium, indium, niobium (columbium), rhenium; waste & scrap; powders”) and only few national statistics provide more details by splitting the HS codes in national sub codes (i.e. 81129289 “Unwrought gallium; waste & scrap; powders”) in the European Combined Nomenclature (CN) system).

Data mainly provided by the Global Trade Atlas (GTA) shows exports of unwrought gallium at about 170 – 200 t/a during the last five years (Table 18). Principal exporters were China, Germany and the United Kingdom.

Table 18: Exports of unwrought gallium (HS 81) [in kg] (GTIS 2015, DESTATIS 2015, Asian Metal 2015)

Exports	2010	2011	2012	2013	2014
China	49,000	52,000	35,000	76,700	83,900
Germany	32,500	48,200	40,000	37,600	16,200
Kazakhstan		5,000	10,000	10,000	
Russia	11,000	9,000	1,000		
Slovakia	13,000	10,000	12,000	4,000	8,000
South Korea	6,000	10,000	2,000	5,000	6,000
UK	39,000	75,000	21,000	14,000	25,000
Ukraine	17,000	11,000	3,000	11,000	10,000
Total Exports	**167,500**	**220,200**	**124,000**	**158,300**	**149,100**

35 % of China’s gallium exports in 2013 were shipped to the United Kingdom, followed by Japan (28 %) and Germany (17 %) (Roskill 2014). In February 2015, China exports totaled 6,216 kg of “Wrough gallium and products” (HS Code 81129990), of which 2,000 kg were shipped to South Korea, 1,900 kg to Germany, and 1,201 kg to Japan. This was a decrease of 29.8 % compared to December 2014, but an increase of 93.5 % compared to February 2014 (Asian Metal 2015).

Germany exported 162 t of unwrought gallium (HS Code 81129289) in 2014, a sharp decrease of more than 50 % compared to the years before (Table 19, 20). Principal partners were the USA, the United

Kingdom and Switzerland. German imports of unwrought gallium totaled at 382 t in 2014, a decrease of 3.3 % compared to the preceding year. Most of the gallium was imported from China, Slovakia and the United Sates (DESTATIS 2015).

Table 19: Germany: Imports of unwrought gallium (HS 81129289) [in kg] (DESTATIS 2015)

Imports	2009	2010	2011	2012	2013	2014
Austria					100	
Belgium			800	700	1,000	400
Canada		300				
China		1,400	800	3,000	14,700	20,900
France		200	200	100	100	100
Hungary	1,000	1,700	1,300			900
Japan		100	2,600		100	900
Netherlands		400	600	100		
Russia	2,000	900	300			
Slowakia	5,000	13,000	10,300	11,900	1,600	7,800
South Korea					200	1,100
UK	4,000	10,900	18,500	14,600	20,900	2,400
Ukraine	1,000	1,000	700	100	700	400
USA	4,000	6,200	10,300	2,900	100	3,300
Total Imports	**17,000**	**36,100**	**46,400**	**33,400**	**39,500**	**38,200**

Table 20: Germany: Exports of unwrought gallium (HS 81129289) [in kg] (DESTATIS 2015)

Exports	2009	2010	2011	2012	2013	2014
Australia				100	100	100
Austria		100	100	100	100	100
Canada			200			
China		800			100	100
Denmark		100			100	100
France		100	100		100	100
Italy		100	300	100	100	100
Japan				100	100	100
Luxembourg		100	200	100	100	100
Netherlands		100				
Poland				1,300	300	100
Singapure			100	100		
Slowakia			7,600	100	6,100	200
South Korea				100	200	300
Spain		100			100	
Switzerland	1,000	3,600	5,000	4,500	3,300	200
UK	9,000	14,600	900	9,400	14,100	7,000
USA	7,000	12,800	33,700	24,000	12,700	7,600
Total Exports	**17,000**	**32,500**	**48,200**	**40,000**	**37,600**	**16,200**

The United States imported 57 t of unwrought gallium in 2014, an increases of more than 61 % compared to 2013, Imports came from Germany (36 %), the United Kingdom (24 %), China (23 %), and the Ukraine (6 %).

16 Outlook for gallium supply and demand

Consumption of gallium rose at a CAGR of 2.47 % during the last decade but it is estimated that a growing demand in all sectors of the semiconductor/semi-insulator market will lead to higher growth rates in the coming years.

The use of LEDs, especially in general lighting applications will be the market with the most growth potential. The highest growth is forecast to be in the Asia Pacific region, particularly in China. According to Jaskula (2015b) China's LED lighting market will more than double from 3.1 billion US$ in 2013 to 4.7 billion US$ in 2017, and the of LED share of the lighting market in China will increase from 9.6 % to 18 % during this time, Roskill (2014) estimates a CAGR of 16,3 % for the worldwide general lighting sector from 2014 to 2020.

Consumption of gallium (GaAs and GaN) in power management devices (MMICs, FETs) is estimated to increase at a CAGR of 3.2 % from 2014 to 2020 (Roskill 2014) resulting mainly in increased production of smart phones, tablet computers, and modern LCD TVs. As for the LED market, highest growth rates are forecast to the Asia Pacific region, especially to China.

Consumption of gallium in photovoltaic applications (CIGS) is estimated to increase at a CAGR of 4 % from 2014 to 2020 (Roskill 2014).

Based on the CAGR of 5.9 % for total gallium (Roskill 2014) consumption would amount to about 402 t in 2020 and 535 t in 2025, an increase of 40 %, respectively 88 % compared to 2014.

Presently, the capacity for the production of primary gallium is estimated at about 680 t/a, So there is more than sufficient gallium to meet any likely demand within the next ten years, even on reduced capacity usage.

In addition to this, there are a few projects, which would bring additional capacities to the market:

- The Canadian Orbite Aluminae Inc. will build a separation facility at its high-purity alumina (HPA) plant located in Cap Chat, Quebec, to recover 4N gallium and other rare metals. Production capacity is reported to be 90 t/a of primary crude gallium. Production will start not before 2016 (Côté et al 2012, Jaskula 2015b).
- The Canadian 5N Plus Inc., a producer of high-purity metals and compounds, and Rio Tinto Alcan, a global provider of bauxite, alumina and aluminium has signed a memorandum of understanding (MOU) regarding a project to recover gallium from an alumina production stream at Rio Tinto Alcan's Vaudreuil alumina facility in Quebec (5N Plus 2011).
- Currently, there is no large-scale production of gallium in India. A capacity of merely 55 kg of primary gallium is reported from Hindalco Industries Ltd,'s Renukoot alumina refinery (IMY 2015). There are plans in India to start the production of primary gallium: The National Aluminium Company (NALCO) has invited expressions of interest (EOI) to source technology to build a gallium extraction plant, which is expected to be set up at the company's alumina refinery site in Damanjodi, State of Odisha. The plant will have a capacity of 10 t/a and will produce gallium metal with 99.99 % purity (NALCO 2014).

- The Chinese China Shenhua Energy Company Ltd, is planning to extract gallium from fly ashes of its Heidaigou Coal Mine in the Jungar Coalfield, Inner Mongolia. Gallium is significantly enriched in the no. 6 coal seam of the mine with an average content of 18.8 – 26.0 ppm (Wang et al. 2011). According to company information gallium content is 32 – 37 ppm in the coal and 82 – 87 ppm in the fly ash. Gallium content in the mine is estimated at 857,000 t. Capacity for the production of 4N gallium, followed by higher purities later on, is planned at 600 t/a (personal communication, June, 2015).

Should these new capacities in fact enter the market, it would nearly double the existing capacities.

17 Summary and conclusions

The use of gallium compound based semiconductors has made gallium a high-tech metal in the past decades. The two main applications fields are integrated circuits (ICs, "Microchips") and optoelectronic devices.

Gallium is recovered both as primary production, and secondary from recycled gallium-bearing scrap, mainly from the wastes of the production of GaAs and GaN compound wafers, About 90 % of all primary gallium produced is currently extracted as a by-product of bauxite during the refining of alumina, and only a small amount of gallium is produced as a by-product of zinc extraction from sphalerite ore (ZnS).

Global capacities for the production of crude gallium amounted to 680 t of which more than 80 % are in China, which has ramped up production capacities massively since the end of the 1990s. Outside China the production capacities in Germany, Kazakhstan, South Korea, the Ukraine, Russia, Japan, and Hungary add up to about 123 t. World primary gallium production is estimated at 440 t in 2014, with China, Germany, and Ukraine being the leading producers.

Worldwide secondary capacities are estimated at 200 t.

Refined gallium production in 2014 was about 170 t. Principal producers of refined gallium from primary material were China, Japan, the United Kingdom, the United States, and Canada. Principal producers of refined gallium from secondary material were Japan, China, the United Kingdom, the United States, Slovakia, and Germany.

Global gallium consumption is estimated at 285 t in 2014. About 90 % of the global gallium demand is used in semi-conducting or semi-insulating (SC/SI) substrates and epitaxial layers for the production of ICs, FETs , and LEDs.

The largest market for gallium is still Japan, but China's demand grew rapidly and is assumed to overtake Japan within the next years.

Since 2003 prices for unwrought gallium (4N) have been relatively stable in a range around 200 US$ only briefly interrupted by peaks in 2007 and 2011.

About 170 and 200 t/a of unwrought gallium was exported during the last five years, Principal exporters were China, Germany and the United Kingdom.

Gallium supply exceeds gallium demand by far, so that the gallium market is over-supplied. There is more than sufficient gallium to meet any likely demand within the next ten years.

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und Rohstoffe

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ISBN: 978-3-943566-33-8