

Rare Earth Markets and Imbedded Demand

DOE/NETL

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What are Rare Earth Elements (REEs)?

Periodic Table of the Elements

Atomic Number

Atomic Mass

Symbol

Name

Electron Shells

Electron Configuration

Element symbol represents state at room temperature.

Solid, Liquid or Gas

1 1A 1A 1 H Hydrogen 1.008 [He]1s ¹	2 2A 2A 4 Be Beryllium 9.012 [He]2s ²	3 3A 3A 5 B Boron 10.811 [He]2s ² 2p ¹	4 4A 4A 6 C Carbon 12.011 [He]2s ² 2p ²	5 5A 5A 7 N Nitrogen 14.007 [He]2s ² 2p ³	6 6A 6A 8 O Oxygen 15.999 [He]2s ² 2p ⁴	7 7A 7A 9 F Fluorine 18.998 [He]2s ² 2p ⁵	8 8A 8A 10 Ne Neon 20.180 [He]2s ² 2p ⁶
11 3A 3A 11 Na Sodium 22.990 [Ne]3s ¹	12 4A 4A 12 Mg Magnesium 24.305 [Ne]3s ²	13 5A 5A 13 Al Aluminum 26.982 [Ne]3s ² 3p ¹	14 6A 6A 14 Si Silicon 28.086 [Ne]3s ² 3p ²	15 7A 7A 15 P Phosphorus 30.974 [Ne]3s ² 3p ³	16 8A 8A 16 S Sulfur 32.066 [Ne]3s ² 3p ⁴	17 9A 9A 17 Cl Chlorine 35.453 [Ne]3s ² 3p ⁵	18 10A 10A 18 Ar Argon 39.948 [Ne]3s ² 3p ⁶
19 4A 4A 19 K Potassium 39.098 [Ar]4s ¹	20 5A 5A 20 Ca Calcium 40.078 [Ar]4s ²	21 6A 6A 21 Sc Scandium 44.956 [Ar]3d ¹ 4s ²	22 7A 7A 22 Ti Titanium 47.88 [Ar]3d ² 4s ²	23 8A 8A 23 V Vanadium 50.942 [Ar]3d ³ 4s ²	24 9A 9A 24 Cr Chromium 51.996 [Ar]3d ⁵ 4s ¹	25 10A 10A 25 Mn Manganese 54.938 [Ar]3d ⁵ 4s ²	26 11A 11A 26 Fe Iron 55.845 [Ar]3d ⁶ 4s ²
27 12A 12A 27 Co Cobalt 58.933 [Ar]3d ⁷ 4s ²	28 13A 13A 28 Ni Nickel 58.693 [Ar]3d ⁸ 4s ²	29 14A 14A 29 Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹	30 15A 15A 30 Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ²	31 16A 16A 31 Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	32 17A 17A 32 Ge Germanium 72.631 [Ar]3d ¹⁰ 4s ² 4p ²	33 18A 18A 33 As Arsenic 74.922 [Ar]3d ¹⁰ 4s ² 4p ³	34 19A 19A 34 Se Selenium 78.971 [Ar]3d ¹⁰ 4s ² 4p ⁴
35 20A 20A 35 Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	36 21A 21A 36 Kr Krypton 84.798 [Ar]3d ¹⁰ 4s ² 4p ⁶	37 22A 22A 37 Rb Rubidium 85.468 [Kr]4d ¹ 5s ¹	38 23A 23A 38 Sr Strontium 87.62 [Kr]4d ² 5s ²	39 24A 24A 39 Y Yttrium 88.906 [Kr]4d ¹ 5s ²	40 25A 25A 40 Zr Zirconium 91.224 [Kr]4d ² 5s ²	41 26A 26A 41 Nb Niobium 92.906 [Kr]4d ⁴ 5s ¹	42 27A 27A 42 Mo Molybdenum 95.95 [Kr]4d ⁵ 5s ¹
43 28A 28A 43 Tc Technetium 98.907 [Kr]4d ⁵ 5s ²	44 29A 29A 44 Ru Ruthenium 101.07 [Kr]4d ⁷ 5s ¹	45 30A 30A 45 Rh Rhodium 101.07 [Kr]4d ⁸ 5s ¹	46 31A 31A 46 Pd Palladium 106.42 [Kr]4d ¹⁰	47 32A 32A 47 Ag Silver 107.868 [Kr]4d ¹⁰ 5s ¹	48 33A 33A 48 Cd Cadmium 112.414 [Kr]4d ¹⁰ 5s ²	49 34A 34A 49 In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p ¹	50 35A 35A 50 Sn Tin 118.711 [Kr]4d ¹⁰ 5s ² 5p ²
51 36A 36A 51 Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³	52 37A 37A 52 Te Tellurium 127.6 [Kr]4d ¹⁰ 5s ² 5p ⁴	53 38A 38A 53 I Iodine 126.904 [Kr]4d ¹⁰ 5s ² 5p ⁵	54 39A 39A 54 Xe Xenon 131.29 [Kr]4d ¹⁰ 5s ² 5p ⁶	55 40A 40A 55 Cs Cesium 132.905 [Xe]6s ¹	56 41A 41A 56 Ba Barium 137.328 [Xe]6s ²	57 42A 42A 57 La Lanthanum 138.905 [Xe]5d ¹ 6s ²	58 43A 43A 58 Ce Cerium 140.12 [Xe]4f ¹ 5d ¹ 6s ²
59 44A 44A 59 Pr Praseodymium 140.908 [Xe]4f ³ 6s ²	60 45A 45A 60 Nd Neodymium 144.24 [Xe]4f ⁴ 6s ²	61 46A 46A 61 Pm Promethium 144.913 [Xe]4f ⁵ 6s ²	62 47A 47A 62 Sm Samarium 150.36 [Xe]4f ⁶ 6s ²	63 48A 48A 63 Eu Europium 151.964 [Xe]4f ⁷ 6s ²	64 49A 49A 64 Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ²	65 50A 50A 65 Tb Terbium 158.925 [Xe]4f ⁹ 6s ²	66 51A 51A 66 Dy Dysprosium 162.50 [Xe]4f ¹⁰ 6s ²
67 52A 52A 67 Ho Holmium 164.930 [Xe]4f ¹¹ 6s ²	68 53A 53A 68 Er Erbium 167.259 [Xe]4f ¹² 6s ²	69 54A 54A 69 Tm Thulium 168.934 [Xe]4f ¹³ 6s ²	70 55A 55A 70 Yb Ytterbium 173.054 [Xe]4f ¹⁴ 6s ²	71 56A 56A 71 Lu Lutetium 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ²	72 57A 57A 72 Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ²	73 58A 58A 73 Ta Tantalum 180.948 [Xe]4f ¹⁴ 5d ³ 6s ²	74 59A 59A 74 W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ²
75 60A 60A 75 Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ²	76 61A 61A 76 Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ²	77 62A 62A 77 Ir Iridium 192.22 [Xe]4f ¹⁴ 5d ⁷ 6s ²	78 63A 63A 78 Pt Platinum 195.085 [Xe]4f ¹⁴ 5d ⁹ 6s ¹	79 64A 64A 79 Au Gold 196.967 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	80 65A 65A 80 Hg Mercury 200.592 [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	81 66A 66A 81 Tl Thallium 204.383 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	82 67A 67A 82 Pb Lead 207.2 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²
83 68A 68A 83 Bi Bismuth 208.980 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	84 69A 69A 84 Po Polonium 209 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	85 70A 70A 85 At Astatine 209 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	86 71A 71A 86 Rn Radon 222.018 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶	87 72A 72A 87 Fr Francium 223.020 [Rn]7s ¹	88 73A 73A 88 Ra Radium 226.025 [Rn]7s ²	89-103 74A 74A 89-103 Lanthanide Series Actinide Series	104 75A 75A 104 Rf Rutherfordium 261 [Rn]5f ¹⁴ 6d ² 7s ²
105 76A 76A 105 Db Dubnium 262 [Rn]5f ¹⁴ 6d ³ 7s ²	106 77A 77A 106 Sg Seaborgium 266 [Rn]5f ¹⁴ 6d ⁴ 7s ²	107 78A 78A 107 Bh Bohrium 264 [Rn]5f ¹⁴ 6d ⁵ 7s ²	108 79A 79A 108 Hs Hassium 269 [Rn]5f ¹⁴ 6d ⁶ 7s ²	109 80A 80A 109 Mt Meitnerium 268 [Rn]5f ¹⁴ 6d ⁷ 7s ²	110 81A 81A 110 Ds Darmstadtium 269 [Rn]5f ¹⁴ 6d ⁸ 7s ²	111 82A 82A 111 Rg Roentgenium 272 [Rn]5f ¹⁴ 6d ⁹ 7s ²	112 83A 83A 112 Cn Copernicium 277 [Rn]5f ¹⁴ 6d ¹⁰ 7s ²
113 84A 84A 113 Uut Ununtrium 288 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹	114 85A 85A 114 Fl Flerovium 289 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	115 86A 86A 115 Uup Ununpentium 289 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ³	116 87A 87A 116 Lv Livermorium 293 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴	117 88A 88A 117 Uus Ununseptium 294 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵	118 89A 89A 118 Uuo Ununoctium 294 [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶		

Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Metalloid

Nonmetal

Halogen

Noble Gas

Lanthanide

Actinide

Average total
crustal
concentration =
184 ppm
*Wedephol, 1995

Uses for Rare Earth Elements



21 Sc Scandium 44.956 [Ar]3d ¹ 4s ²	57 La Lanthanum 138.905 [Xe]5d ¹ 6s ²	58 Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ²	59 Pr Praseodymium 140.908 [Xe]4f ³ 6s ²	60 Nd Neodymium 144.243 [Xe]4f ⁴ 6s ²	61 Pm Promethium 144.913 [Xe]4f ⁵ 6s ²	62 Sm Samarium 150.36 [Xe]4f ⁶ 6s ²	63 Eu Europium 151.964 [Xe]4f ⁷ 6s ²	64 Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ²	65 Tb Terbium 158.925 [Xe]4f ⁹ 6s ²	66 Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ²	67 Ho Holmium 164.930 [Xe]4f ¹¹ 6s ²	68 Er Erbium 167.259 [Xe]4f ¹² 6s ²	69 Tm Thulium 168.934 [Xe]4f ¹³ 6s ²	70 Yb Ytterbium 173.055 [Xe]4f ¹⁴ 6s ²	71 Lu Lutetium 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ²
39 Y Yttrium 88.906 [Kr]4d ¹ 5s ²	89 Ac Actinium 227.028 [Rn]6d ¹ 7s ²	90 Th Thorium 232.038 [Rn]6d ² 7s ²	91 Pa Protactinium 231.036 [Rn]5f ² 6d ¹ 7s ²	92 U Uranium 238.029 [Rn]5f ³ 6d ¹ 7s ²	93 Np Neptunium 237.048 [Rn]5f ⁴ 6d ¹ 7s ²	94 Pu Plutonium 244.064 [Rn]5f ⁶ 7s ²	95 Am Americium 243.061 [Rn]5f ⁷ 7s ²	96 Cm Curium 247.070 [Rn]5f ⁷ 6d ¹ 7s ²	97 Bk Berkelium 247.070 [Rn]5f ⁹ 7s ²	98 Cf Californium 251.080 [Rn]5f ¹⁰ 7s ²	99 Es Einsteinium [254] [Rn]5f ¹¹ 7s ²	100 Fm Fermium 257.095 [Rn]5f ¹² 7s ²	101 Md Mendelevium 258.1 [Rn]5f ¹³ 7s ²	102 No Nobelium 259.101 [Rn]5f ¹⁴ 7s ²	103 Lr Lawrencium [262] [Rn]5f ¹⁴ 6d ¹ 7s ²



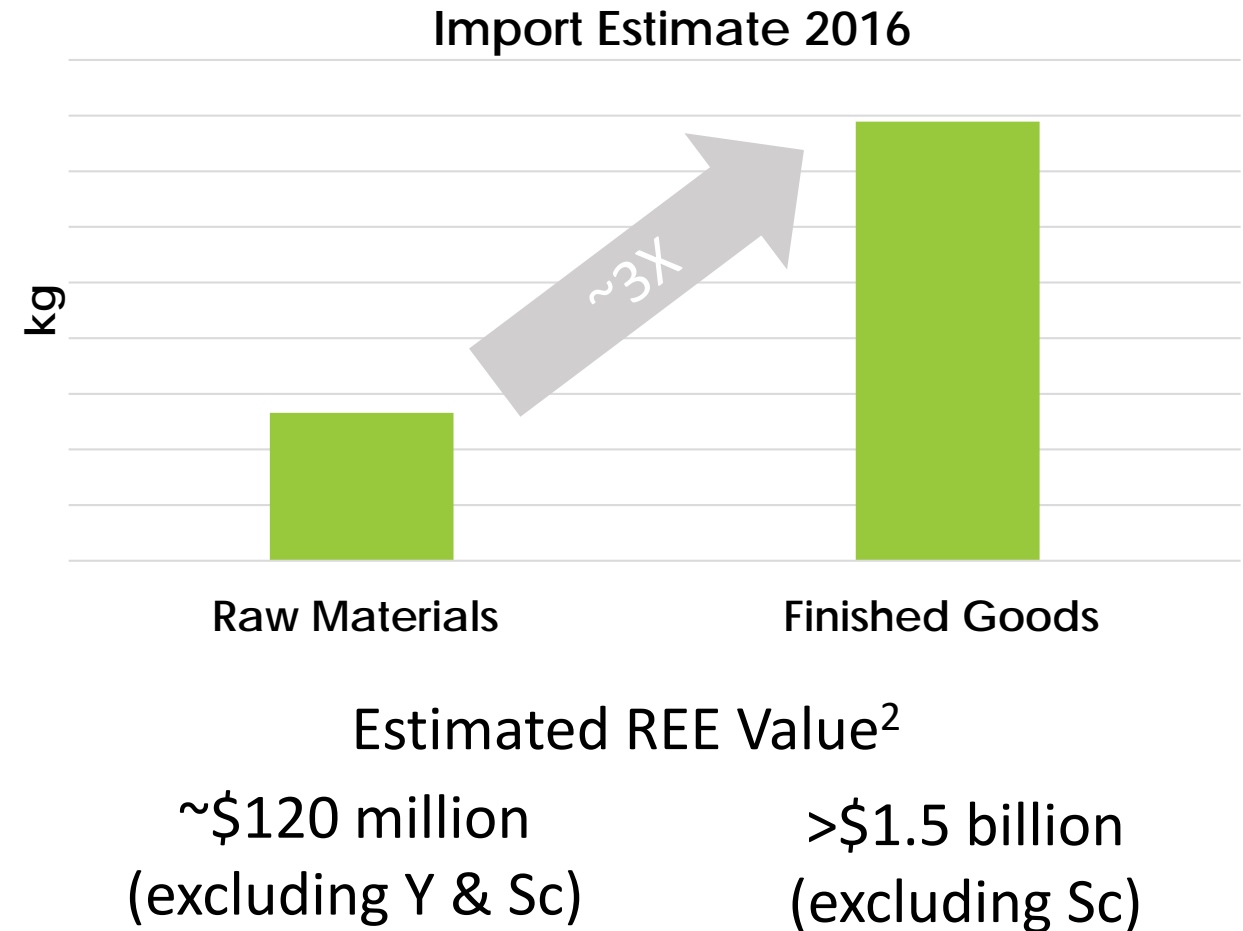
Average total crustal concentration = 184 ppm

*Wedephol, 1995

- **The Annual Global Rare Earth Market was ~\$8 billion in 2018**
 - The US only consumes around 7% of global demand by weight
 - Almost all rare earths are currently being imported
- **The US imported \$2.6 trillion worth of finished products in 2018**
 - The top 4 product groups account for ~50% of the imported value
 - Machinery including computers: \$386.4 billion (14.8% of total imports)
 - Electrical machinery, equipment: \$367.1 billion (14%)
 - Vehicles: \$306.7 billion (11.7%)
 - Mineral fuels including oil: \$241.4 billion (9.2%)

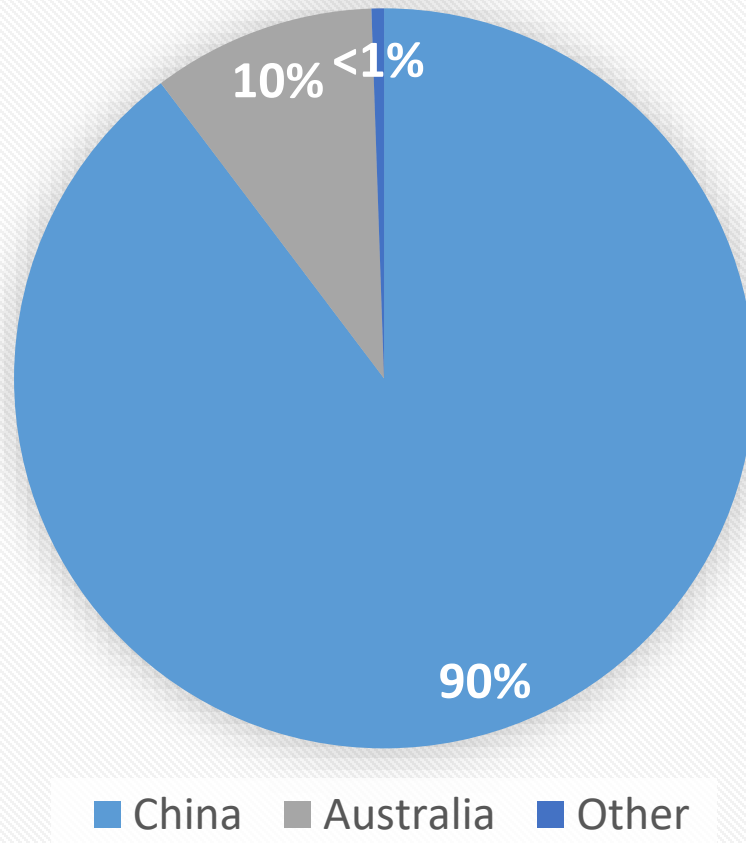
US REE Import Estimates

- US imported ~\$160 million worth of rare earth compounds and metals (excluding Yttrium and Scandium) in 2018¹
 - The estimated distribution by end use: catalysts, 60%; ceramics and glass, 15%; metallurgical applications and alloys, 10%; polishing, 10%; and other, 5%.
- The majority of REE's imported into the US come in the finished goods, and not as a raw material



Global Market

Estimated Global REE Production
2017

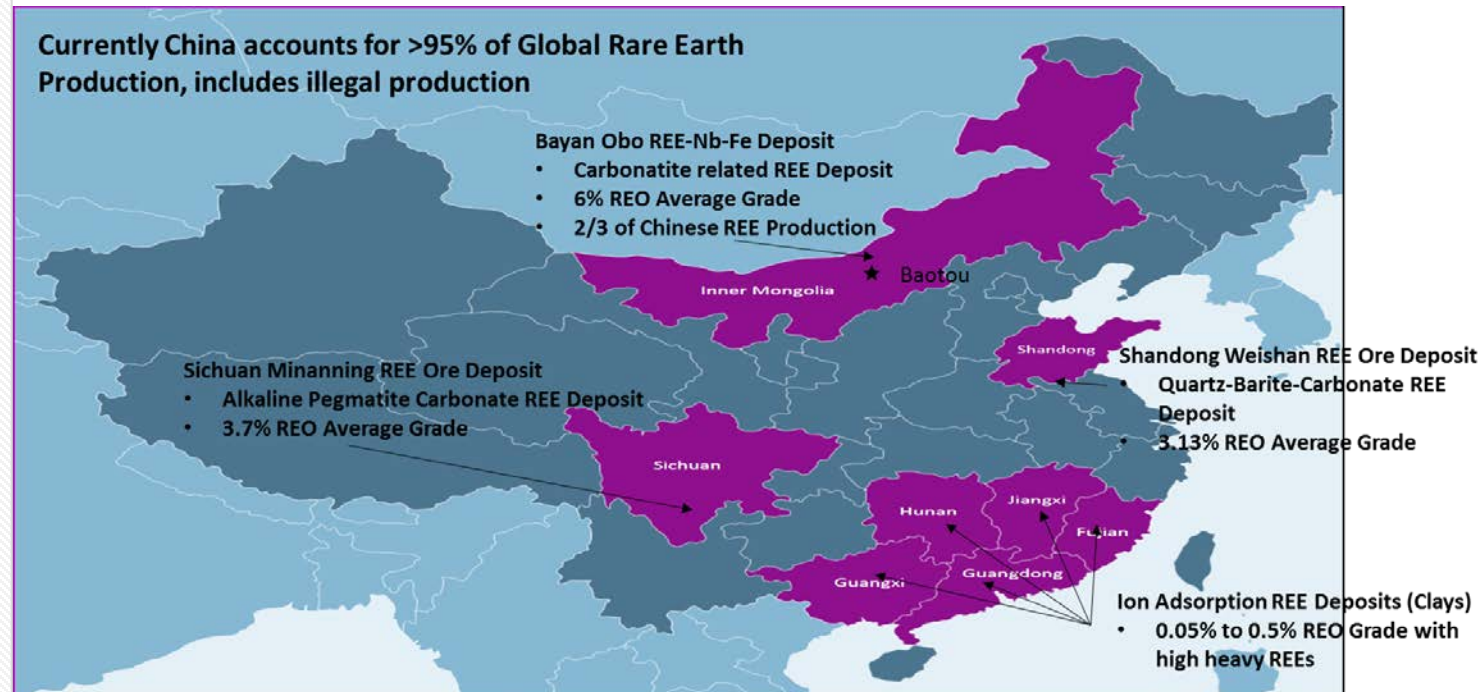


Global Production

- Total REO Production Estimated at ~180,000 tonne/year

Global Demand

- Total REO Demand Estimated at ~150,000 tonne/year
- US accounts for ~11% of Global Demand



- **Lynas' LAMP facility in Malaysia facing increased government scrutiny around handling of waste material**
- **China has become a net importer of REEs associated with permanent magnets**
 - May become a net importer for all rare earths by 2030
- **Inflection point in China due to changing market forces**
 - Miners have “pushed” the market
 - Supply chain beginning to “pull” the market

Market Demand Drivers

Electric Vehicles



- **Electric Vehicles (EV) – BEVs, PHEVs, & HEVs**
 - ~2.2 million EV sold in 2018
 - 93% utilized permanent magnet traction motor¹
 - ~50% sold in China
 - IEA estimates there could be between 125 and 220 million electric vehicles on the road by 2030

Market Demand Drivers

Electric Vehicles

Figure ES 1 • Evolution of the global electric car stock, 2013-17

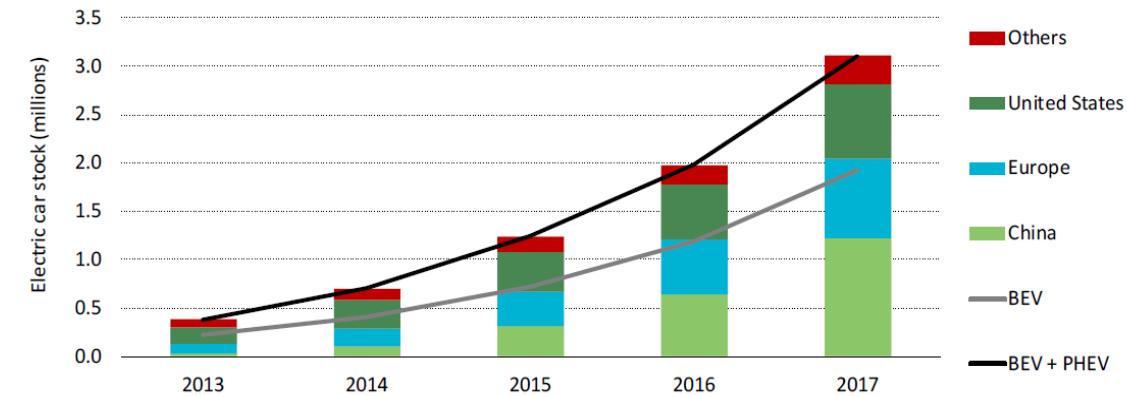
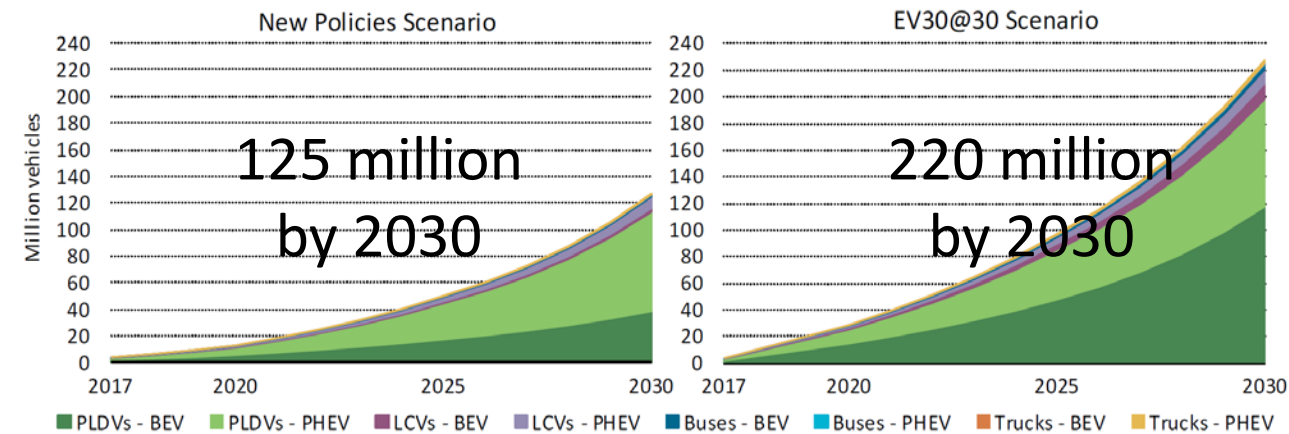


Figure ES 2 • Global EV stock in the New Policies and EV30@30 scenarios, 2017-30



Notes: PLDVs = passenger light duty vehicles; LCVs = light commercial vehicles; BEVs = battery electric vehicles; PHEV = plug-in hybrid electric vehicles.

Table 2.5 • OEM announcements related to electric cars

OEM	2018	2019	2020	2021	2022	2023	2024	2025	2030
BMW	0.14							15-25%	25
BAIC			0.8						
BYD			0.6						
Dongfeng Motor Co					30%				
Ford					40				
Geely			1						
GM		2				20			
Honda									15%
Hyundai-Kia			12						
Mahindra & Mahindra			0.036						
Maruti Suzuki			1						
Mazda			1						
Mercedes-Benz							15-25%	10	
Other Chinese OEMs			7						
PSA					0.9	27			
Renault-Nissan				1	12	20%			
Tesla	100%	0.5	1	1					
Toyota			10						1
Volkswagen			0.4				25%	2.5	80
Volvo		1		5					

Number of sales millions % of electric sales
Number of new EV models Share of models with an electric version

Market Demand Drivers

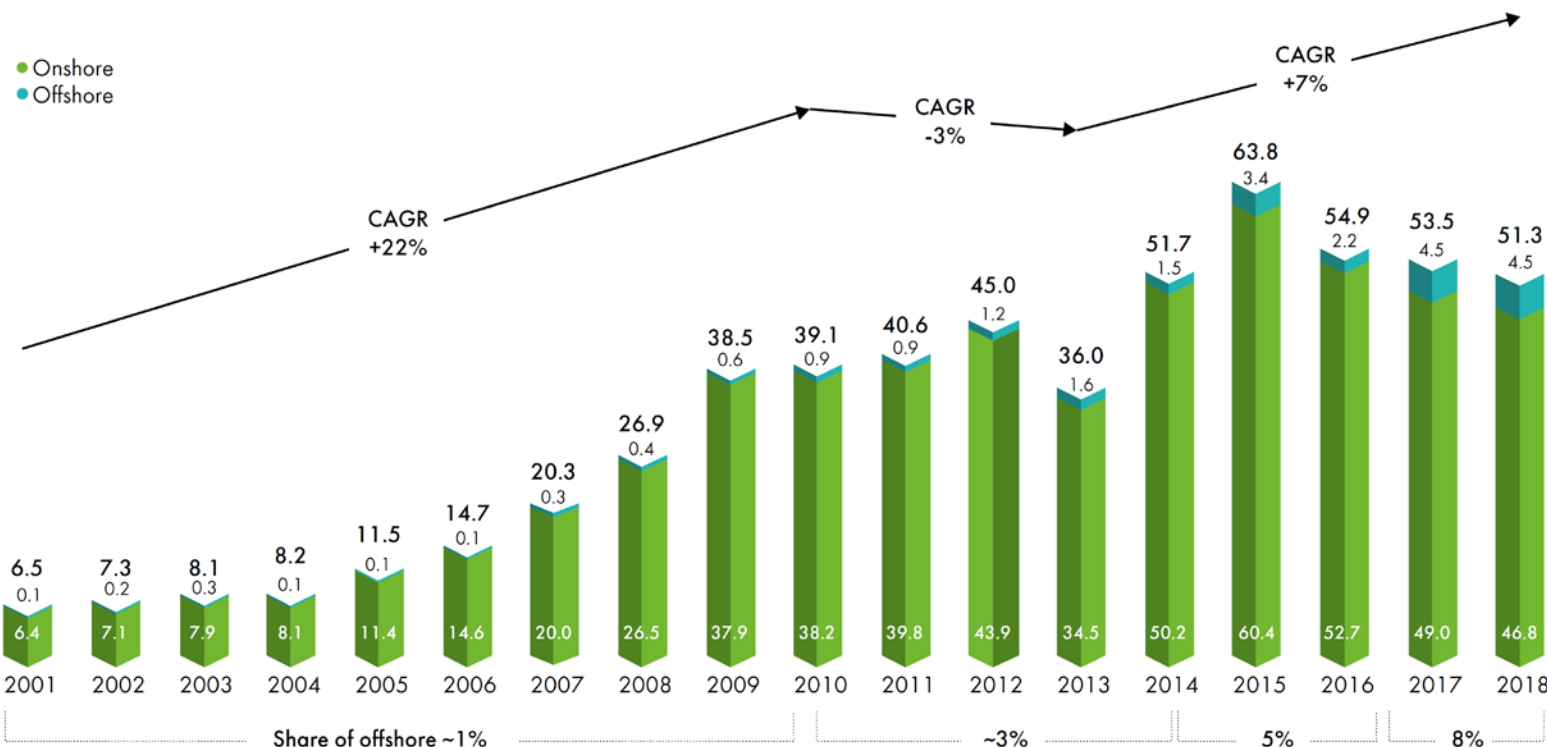
Wind Power Generation

• Wind Power Capacity Worldwide Reaches ~600 GW in 2018

Historic development of new installations
GW

Source: GWEC, Global Wind Report 2018

- ~200 GW in China
- ~100 GW in US
- Offshore ~4%
- By 2025, >10%
 - ~100 GW



- Growing demand for high-tech and green technologies will increase the demand for rare earth elements for foreseeable future
- Changing market drivers could stabilize, and even increase, rare earth market prices for high demand compounds
- Additional uses for more abundant REEs still needed

- REE recovery from coal based feedstock has been proven technically feasible
- Economic feasibility is greatly dependent on market conditions
- Research is occurring to reduce or replace REEs in many finished goods
- Domestic rare earth industry must be coupled with domestic supply chain
- Even with a successful domestic REE industry, China will continue to control the REE market for years to come

Thank you.

Backup Slides

Historic development of total installations

GW

