



中国科学院城市环境研究所

Institute of Urban Environment, CAS

在中国地质科学院的汇报

金属-能源关联(Nexus) 与“碳中和”

陈伟强

中国科学院城市环境研究所

2021年5月28日@北京

汇报提纲

- **人类世(时代)的物质循环**
- **金属-能源关联 与 碳中和**
- **研究团队与工作基础简介**

The Economist

MAY 28TH - JUNE 3RD 2011

Economist.com

Obama, Bibi and peace

Britain's privacy mess

The costly war on cancer

How the brain drain reduces poverty

A soft landing for China

The
Anthropocene
refers to "the current
epoch in which humans
and our societies have
become a **global
geophysical
force**

Welcome to the Anthropocene

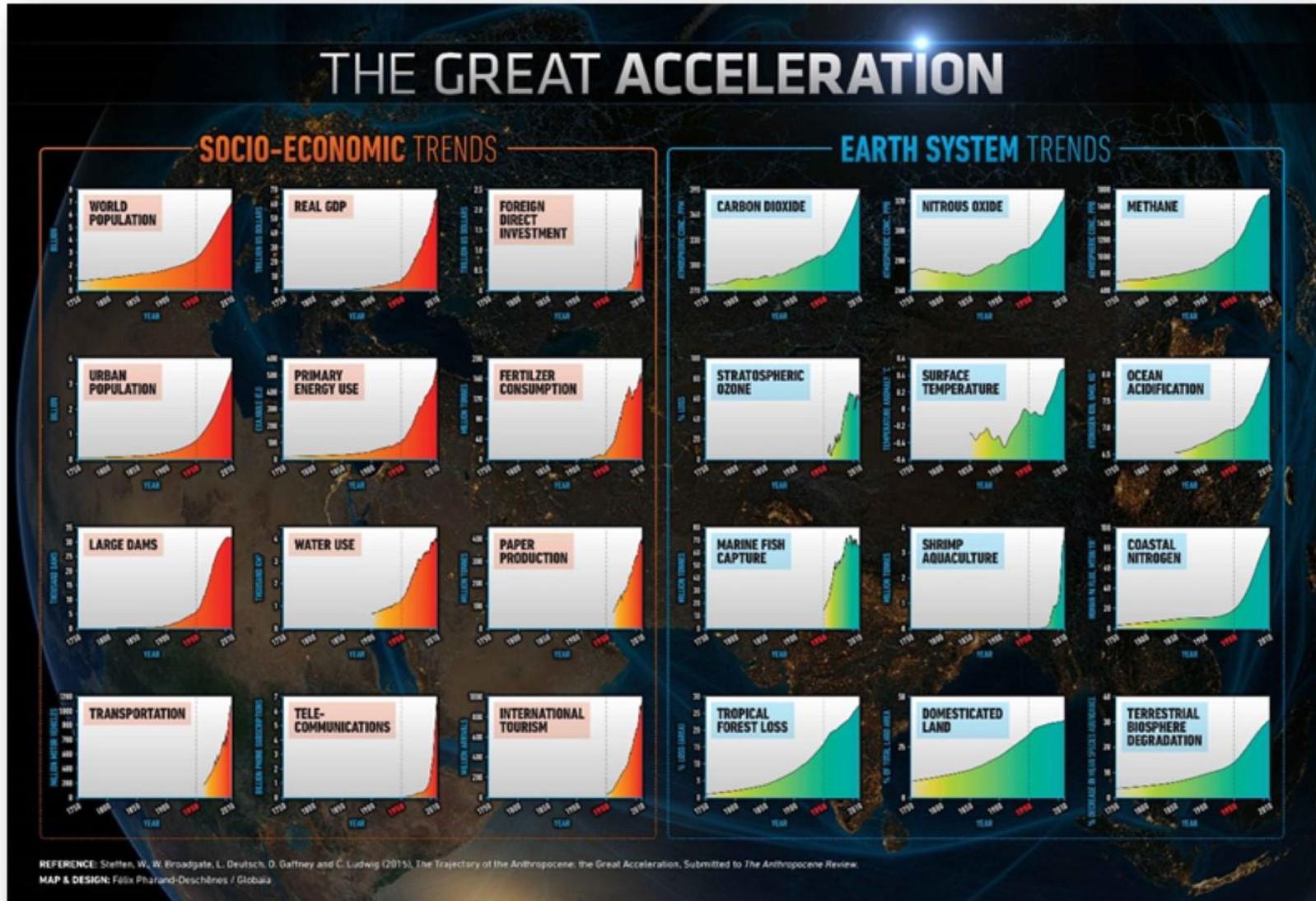


Geology's new age

The Economist, 2011

人类世(Anthropocene) 的大提速(Great Acceleration)

中科院城市环境研究所「物质循环与城市代谢」团队制作



人类改变地球表面的各种循环

中科院城市环境研究所「物质循环与城市代谢」团队制作

ChEN rate to the standard model prediction, they found it to be consistent. They used this result to set stringent new limits on nonstandard neutrino interactions.

Other neutrino experiments planned and running are continuing the search for new physics. One major target of interest is the so-called sterile neutrino (7), a hypothetical fourth neutrino that may be mixed with the other three, but has no other known interactions. Several experiments are being carried out to look for a sudden disappearance of neutrinos from nuclear reactors or radioactive neutrino sources at very short distances. Meanwhile, the Fermi National Accelerator Laboratory (Fermilab), in Batavia, Illinois, is building out its Short-Baseline Neutrino Program, a suite of three detectors at distances of 100 to 500 m along a beam of neutrinos.

Although a discovery of sterile neutrinos would represent a major paradigm shift in particle physics, physicists are still working out the links from the first neutrino breaks the standard model. New experiments, like the Deep Underground Neutrino Experiment (DUNE), are expected to commence in the next 7 to 10 years. DUNE, which will send a beam of neutrinos from Fermilab to a detector located in a decommissioned gold mine in South Dakota, is designed to make precision measurements of several neutrino oscillation parameters. Their main quarry is something known as the CP phase, a number that controls the degree to which the symmetry between matter and antimatter is violated. Many models tie this CP phase to another CP phase that operates at a much higher energy scale, one that was present in the first moments after the Big Bang. Through a proposed process known as leptogenesis, an asymmetry in primordial neutrino interactions causes a slight enhancement of matter over antimatter (8). Because matter and antimatter have a tendency to annihilate one another, this Strepsness would be all that survives to become the stuff of today's universe.

Such essential questions are the heavy stuff of neutrino physics. With a lively experimental program planned and underway, the next 25 years may bring equally lofty answers, and with them more fascinating new questions as well. ■

REFERENCES

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4. A. B. Balantekin, *Phys. Rev. D* **92**, 075002 (2015).
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10.1126/science.1250420



ENVIRONMENT

Microbial mass movements

Wastewater, tourism, and trade are moving microbes around the globe at an unprecedented scale

By Yong-Guan Zhu,¹ Michael Gillings,² Pascal Sleutel,³ Dier Mikkel,⁴ Steve Rasmussen,⁵ Joop Pennings⁶

For several billion years, microorganisms and the genes they carry have mainly been moved by physical forces such as air and water currents. These forces generated biogeographic patterns for microorganisms that are similar to those of animals and plants (1). In the past 100 years, humans have changed these dynamics by transporting large numbers of cells to new locations through waste disposal, tourism, and global transport and by modifying selection pressures at those locations. As a consequence, we are in the midst of a substantial alteration to microbial biogeography. This has the potential to change ecosystem services and biogeochemistry in unpredictable ways.

DISSEMINATION THROUGH WASTEWATER

Disposal of sewage increases the dissemination of both microorganisms and genes

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(see the figure) (2). Globally, some 350,000 km³ of croplands depend on irrigation with urban wastewater, 80% of which undergoes little or no treatment (3). Use of wastewater or manure in agriculture contaminates fruits, vegetables, and farm animals that are then distributed globally (4).

Wastewater carries high densities of microorganisms and their cargo genes. It also contains pollutants with biological effects, including metals, antibiotics, and disinfectants (5). These compounds act as selective agents and stimulate bacterial stress response systems that increase mutation rates in the rod-shaped bacteria. This allows bacterial cells to respond dynamically to changing environments by generating novel variability, conferring adaptive advantages on at least a subset of cells arriving at a new location.

Conduction on different cargo genes amplifies this effect. For example, diverse genes for resistance to metals and disinfectants are often clustered next to multiple antibiotic resistance genes on the same genetic element. Exposure to selective agents maintains these clusters of resistance determinants (2), greatly increasing the probability of selection at a destination and improving the chances of recruitment after dispersal.

THE EXAMPLE OF CLASS 1 INTEGRONS

For a sense of the scale of these effects, consider the clinical class 1 integron. This DNA element acquires foreign genes from the environment and has played a central role in spreading antibiotic resistance between bacterial pathogens. DNA sequencing data show

“随着城市化和高强度集约化农业的发展，人类正以前所未有的速度和规模改变着微生物的全球迁徙和分布”

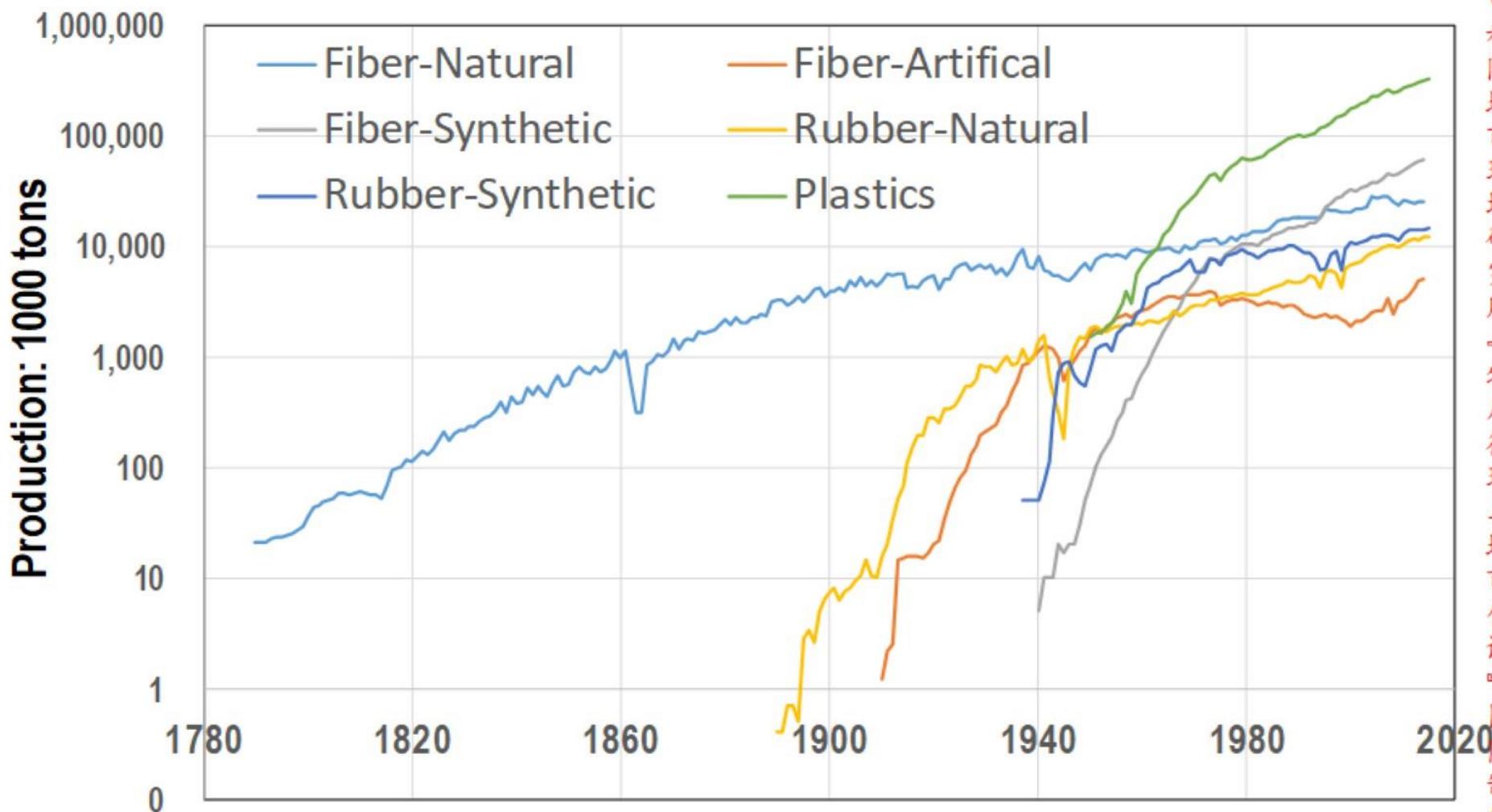
——Zhu et al

Downloaded from http://science.sciencemag.org/ on October 12, 2017

水 能 物 土 生

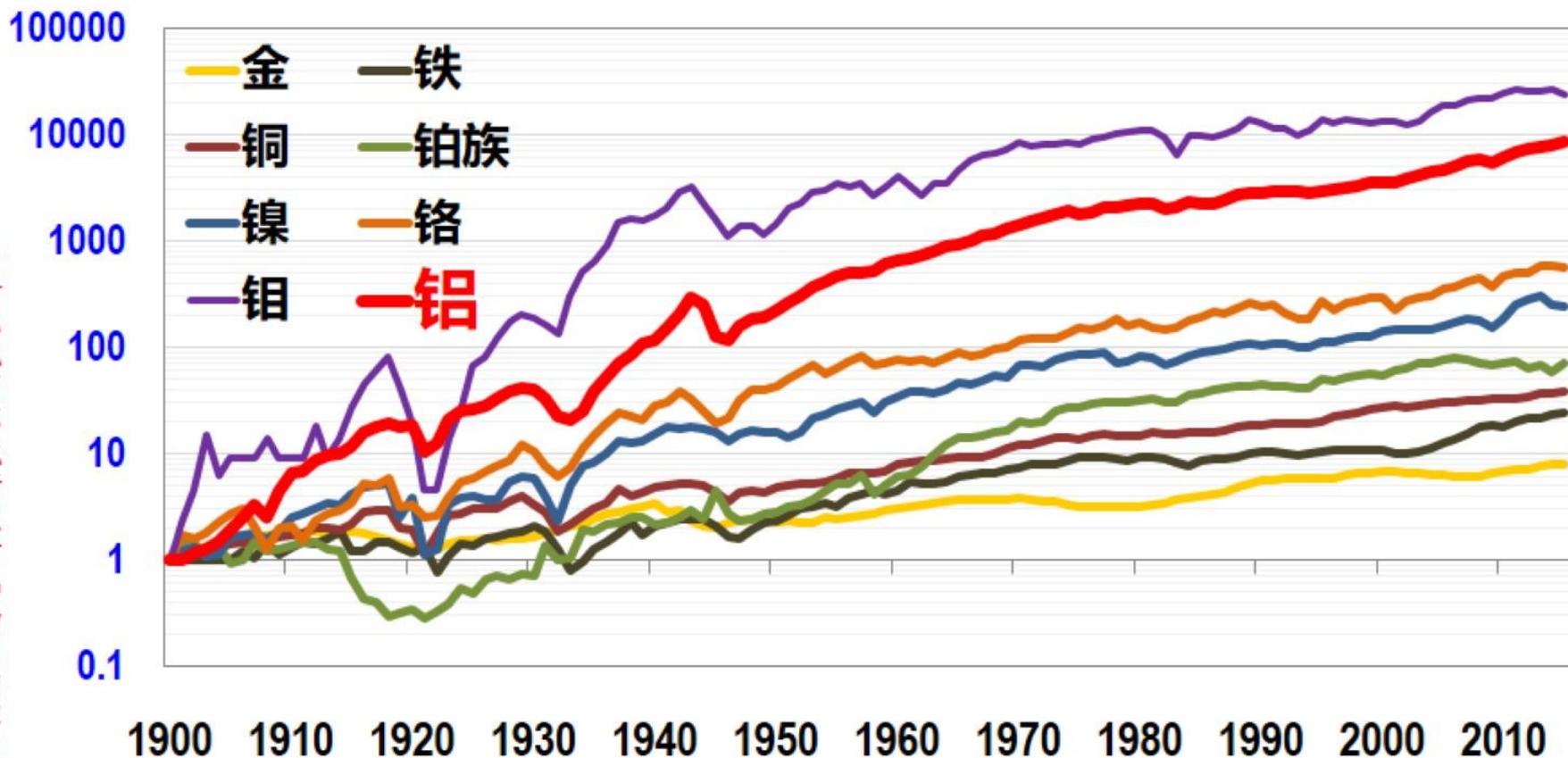
现代社会发展和运行的**物质依赖**
及其与/对经济、生态、环境、技
术和**能源**等因素的关联/影响

塑料和化学品生产的大提速



中科院城市环境研究所「物质循环与城市代谢」团队制作

金属资源生产的大提速

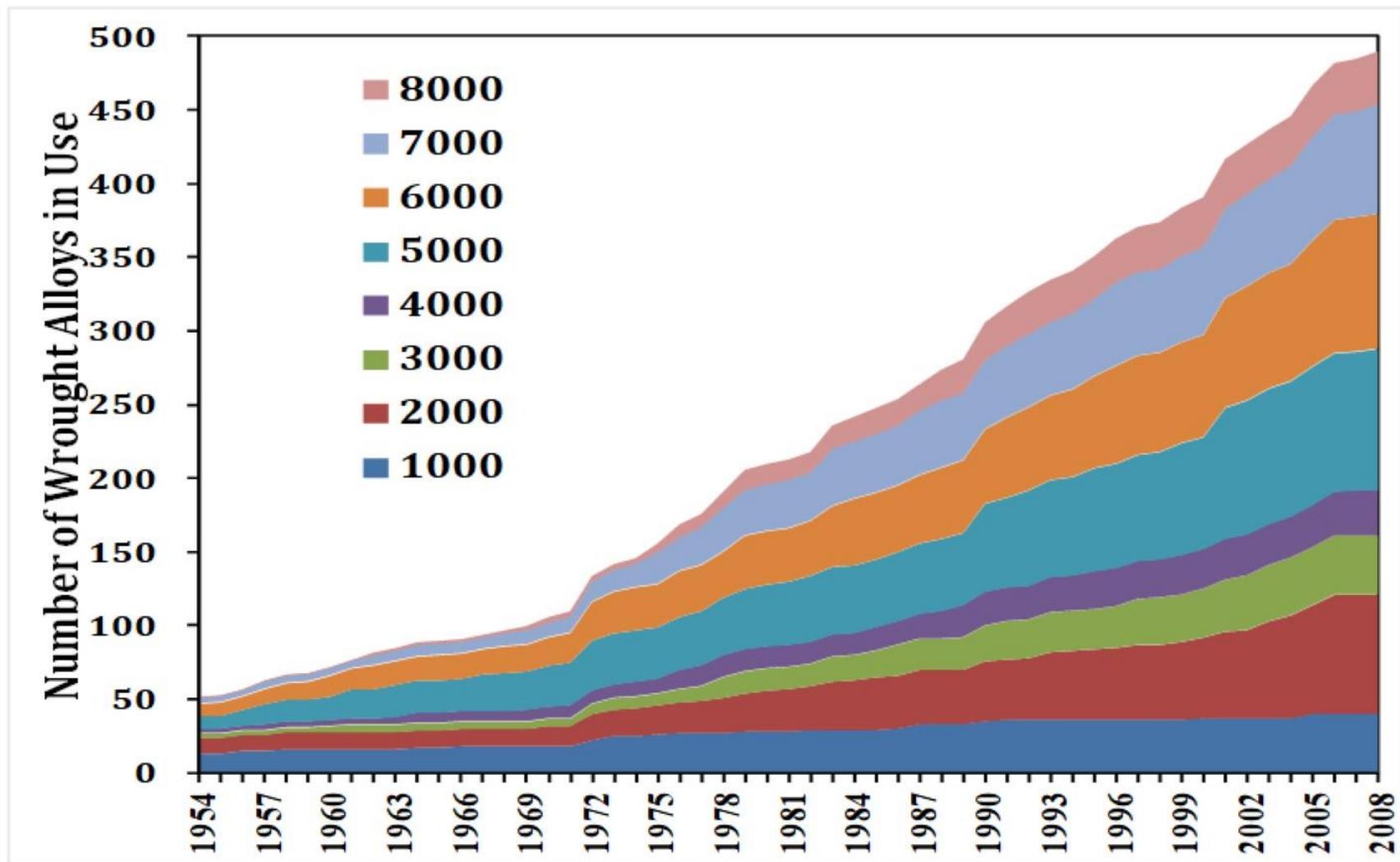


1900-2015年增长倍数

金: 8 铁: 24 铜: 39 铂族: 71
镍: 245 铬: 567 **铝: 8456** 钨: 23500

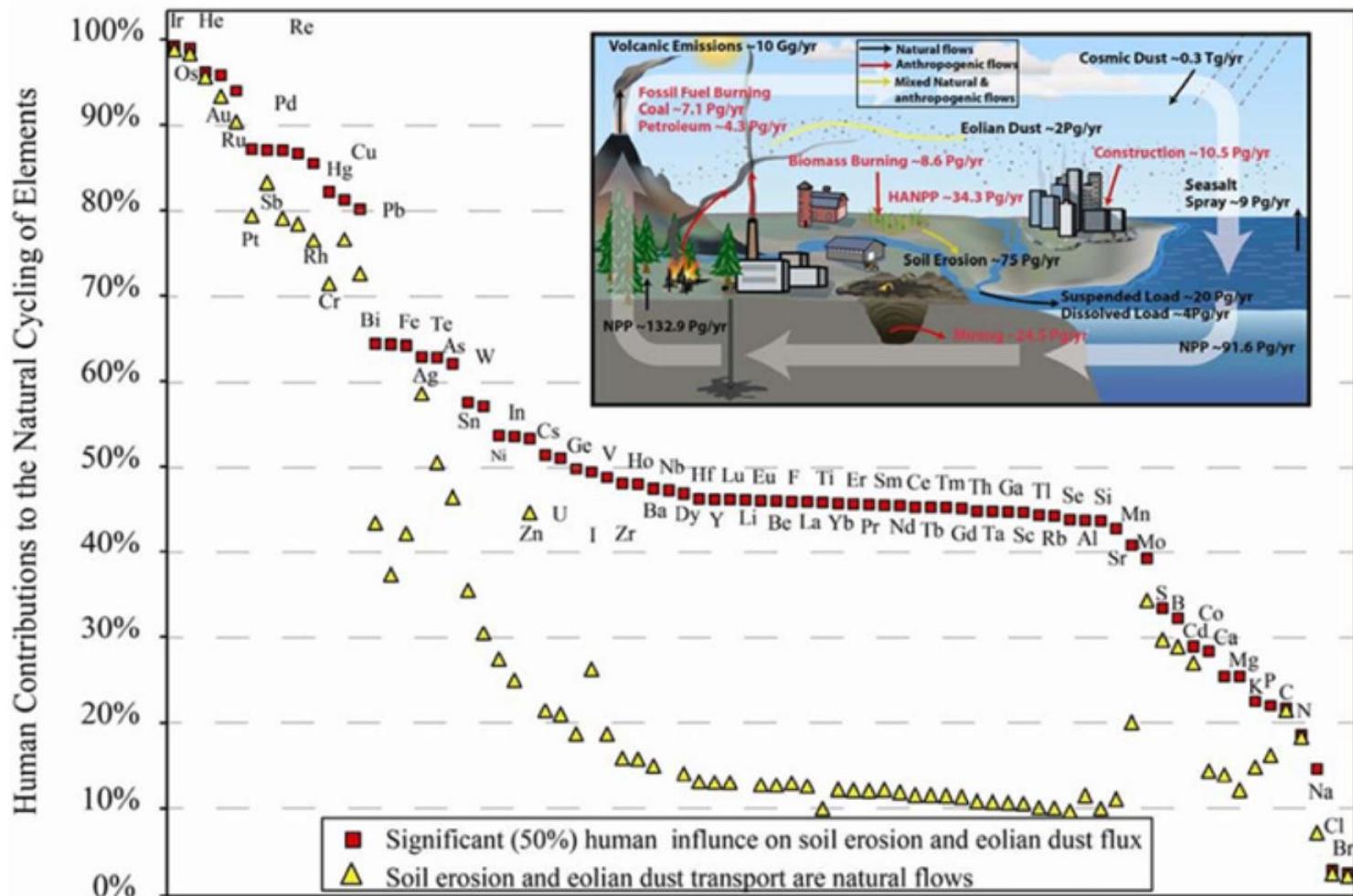
来源: 陈伟强课题组整理

Growing Complexity of Materials Use



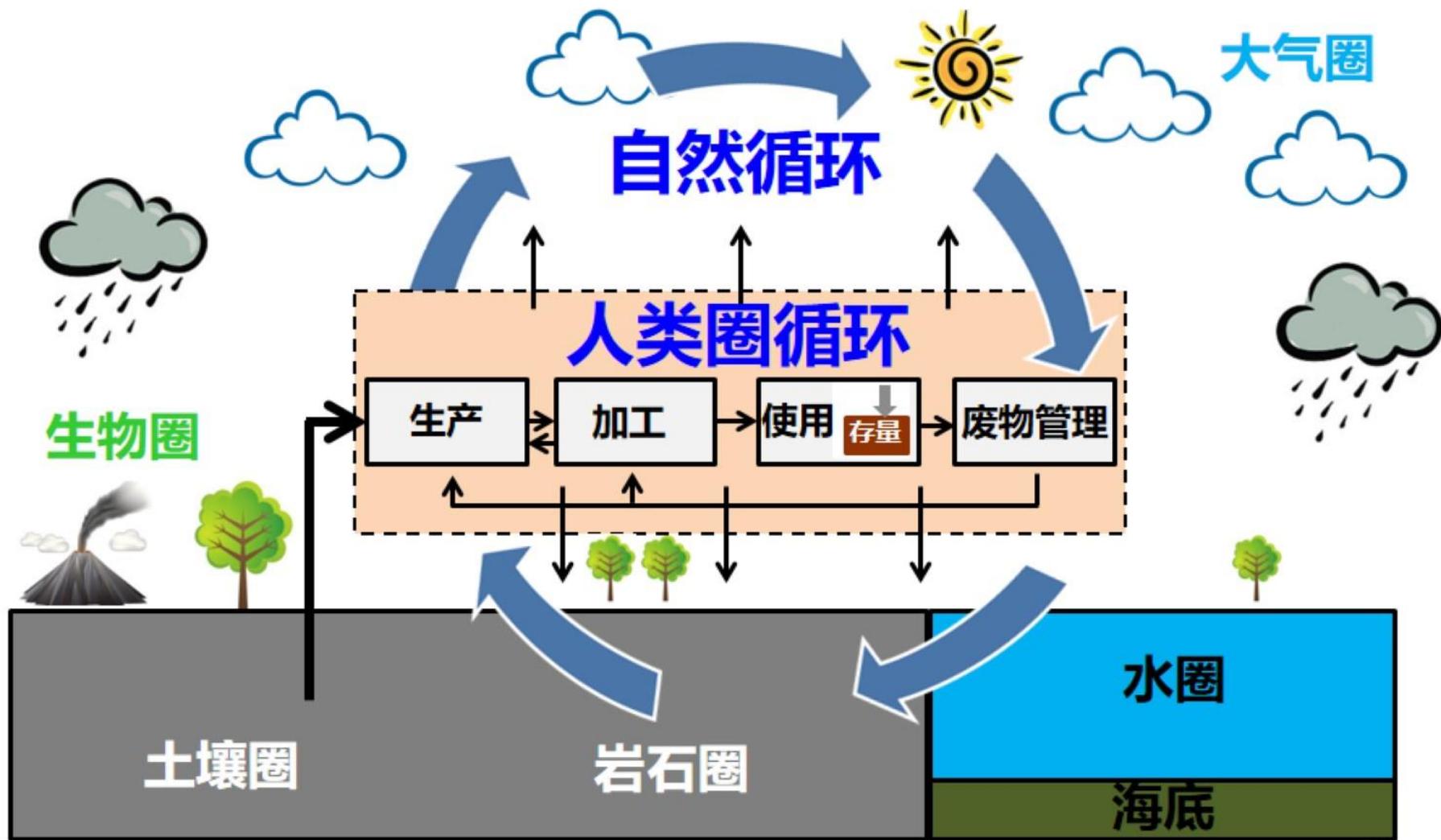
中科院城市环境研究所「物质循环与城市代谢」团队制作

地表的元素循环：人为对比自然



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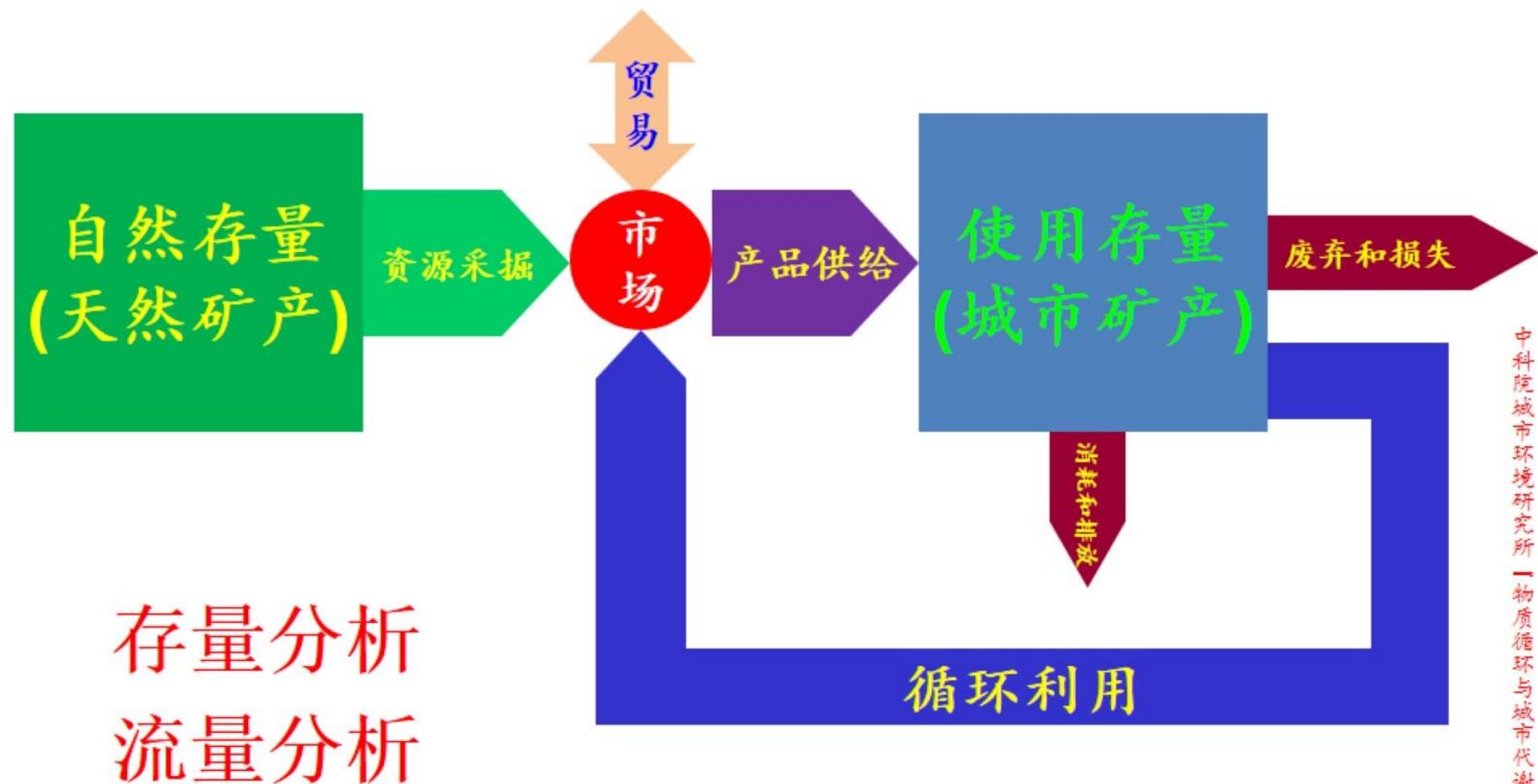
人类圈循环在地表总循环中日益重要



中科院城市环境研究所「物质循环与城市代谢」团队制作

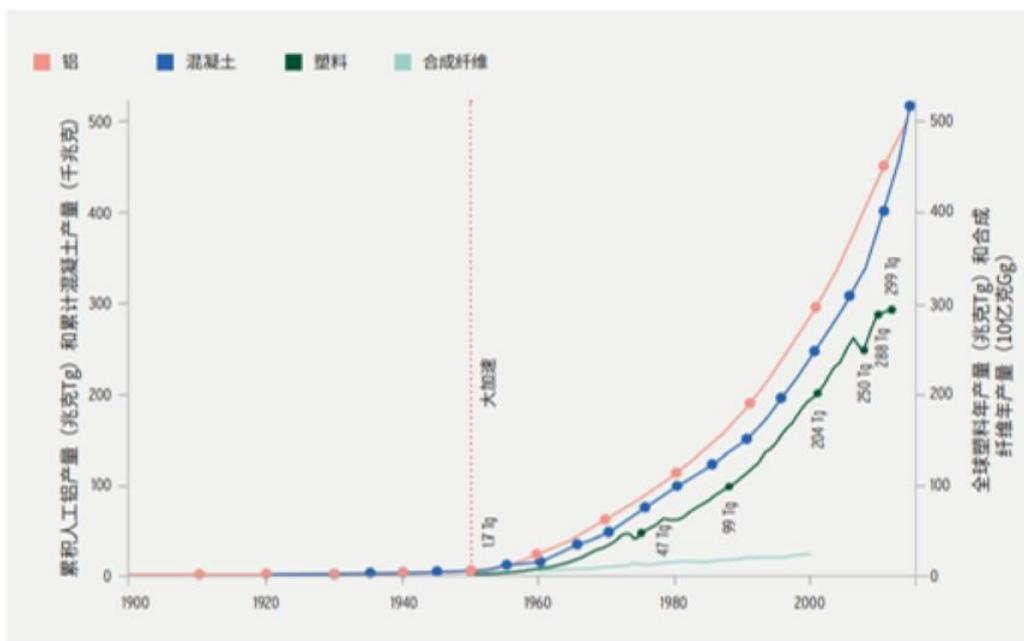
改编自Philip Nuss and Gian Andrea Blengini. *Science of the Total Environment*. 2017.

人为物质循环与经济发展的耦合



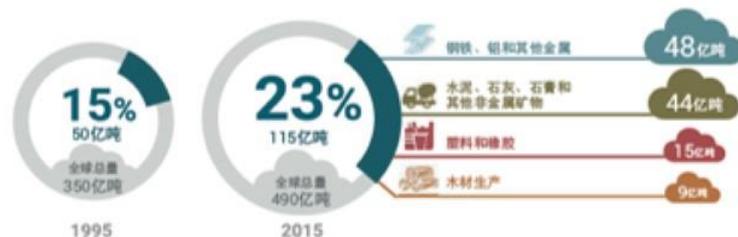
人为物质循环导致的环境影响日益加剧

中科院城市环境研究所「物质循环与城市代谢」团队制作

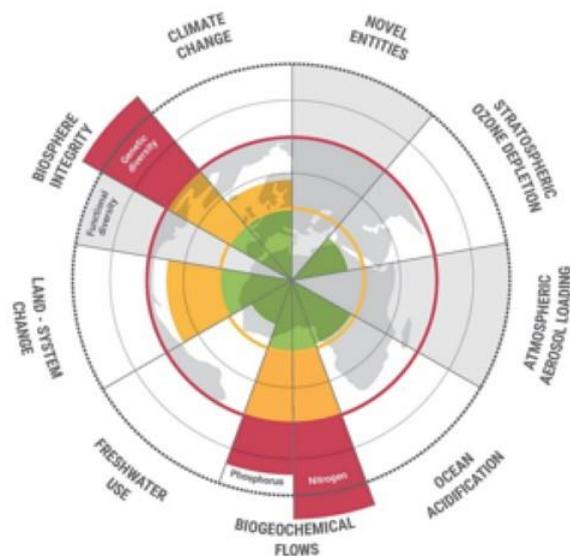


来源: Waters等人 2016.

人类物质使用大加速 -> 人类世



碳排放激增



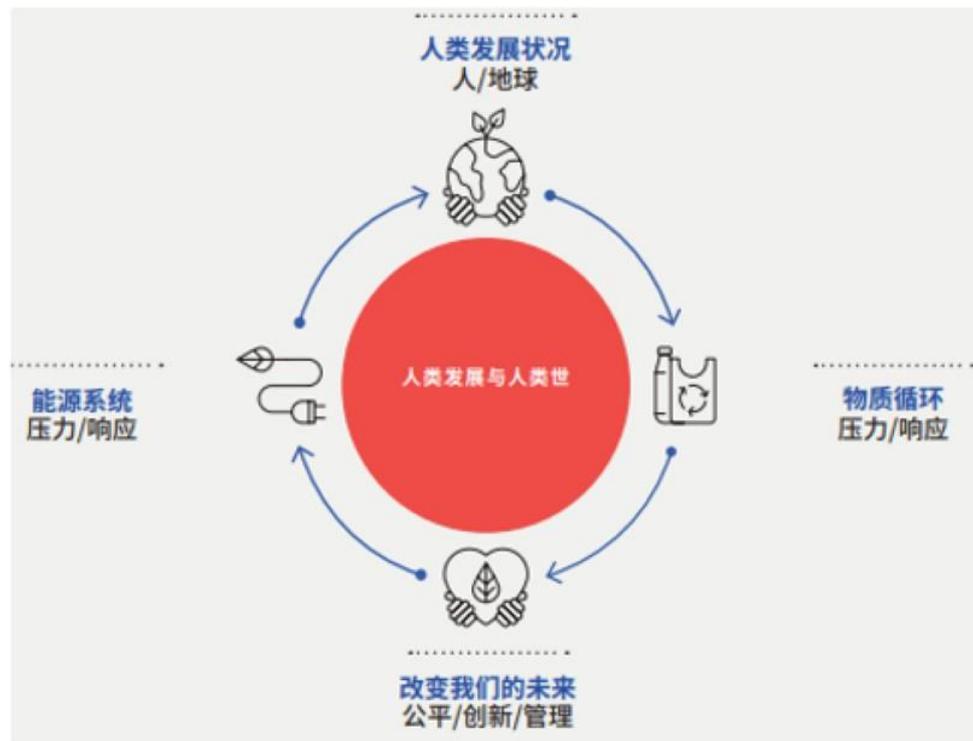
突破地球行星边界

物质循环及其影响被纳入可持续发展研究框架

中科院城市环境研究所「物质循环与城市代谢」团队制作

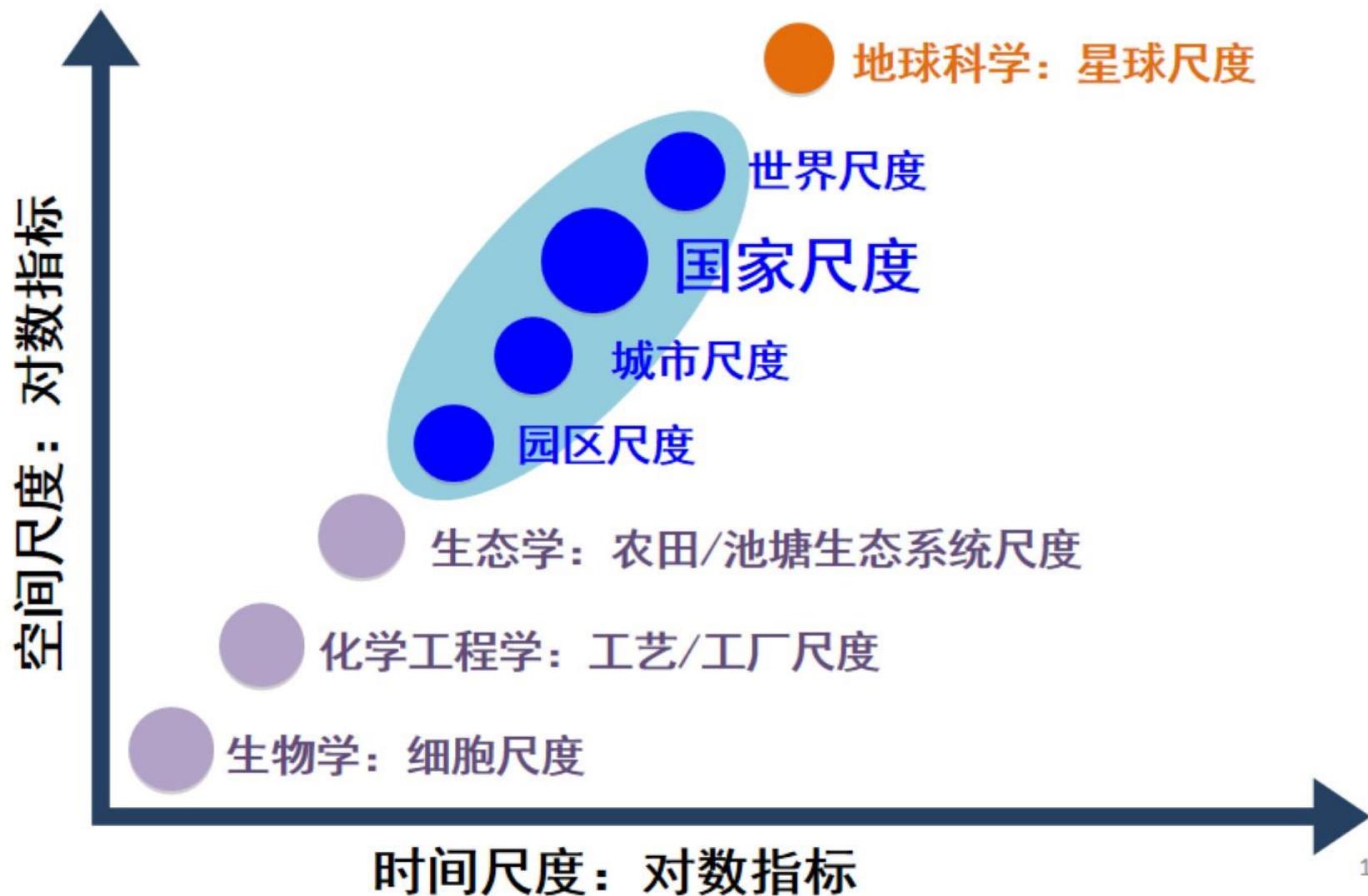


联合国发展署《2020人类发展报告》



物质循环与碳排放成为
衡量各国人类发展指数新标尺

人类圈物质循环研究的时空边界



对象和范围



建筑材料
(水泥/玻璃...)



基本金属
(铜/铁/铝...)



稀贵金属
(钨/铟/镓...)



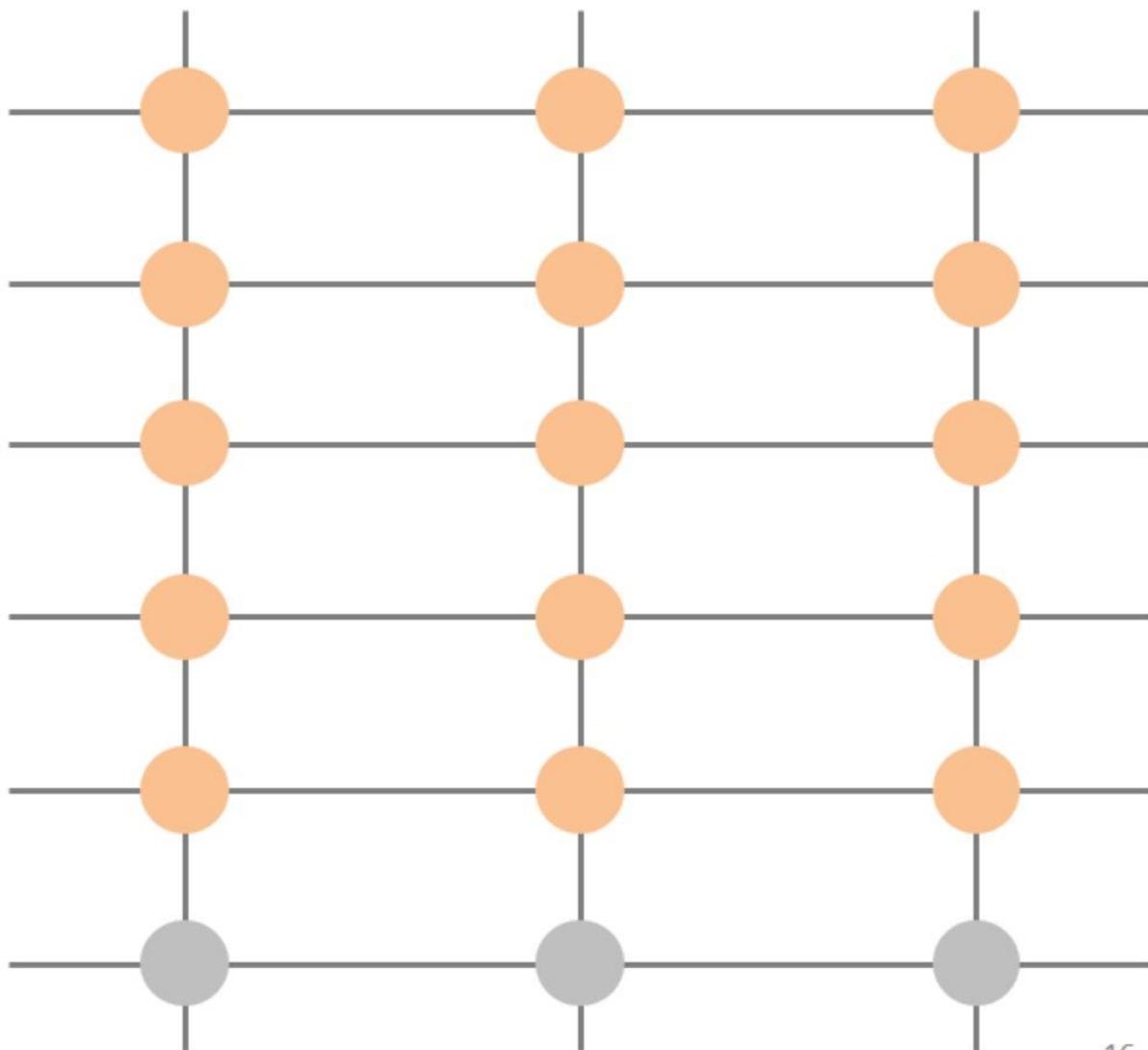
有毒金属
(砷/汞/镉...)



塑料/化学品
(PE/PTA...)

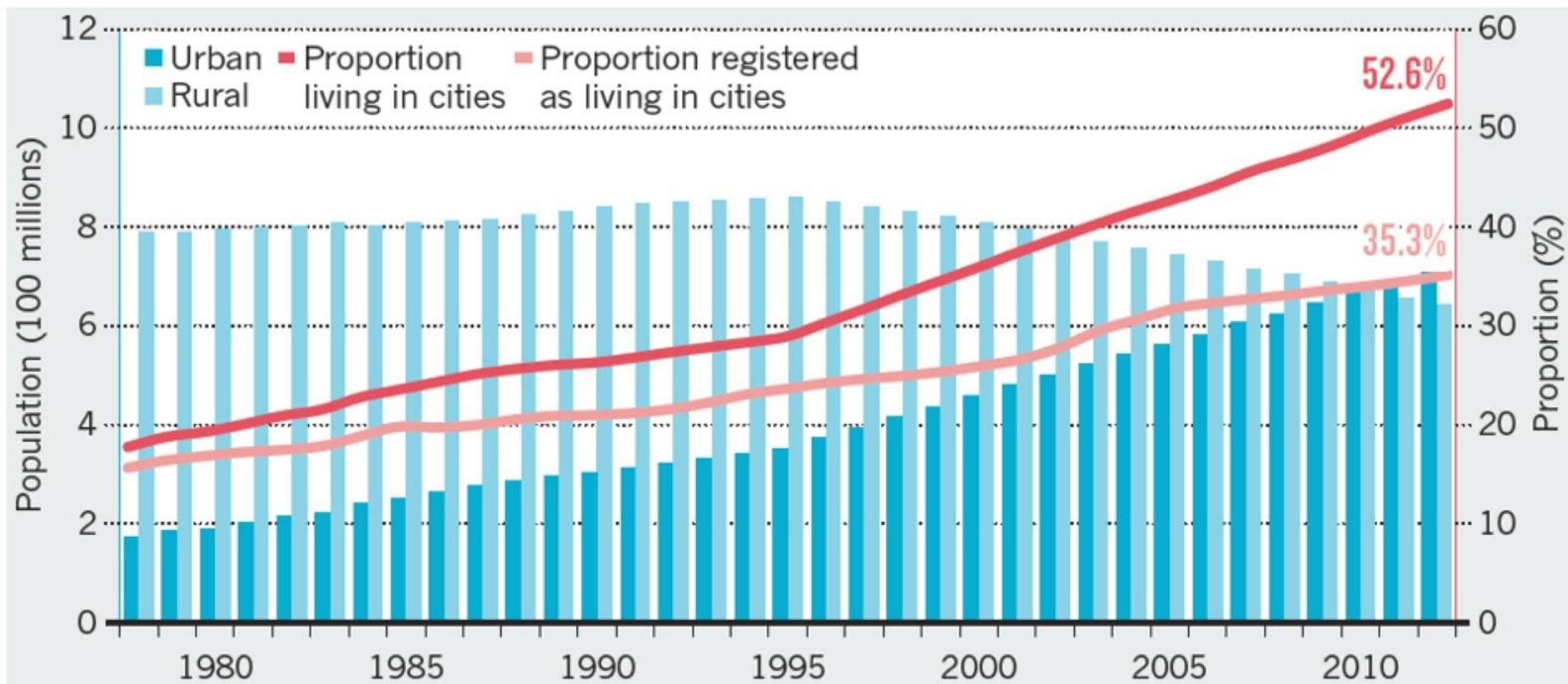


营养元素
(氮/磷/钾...)

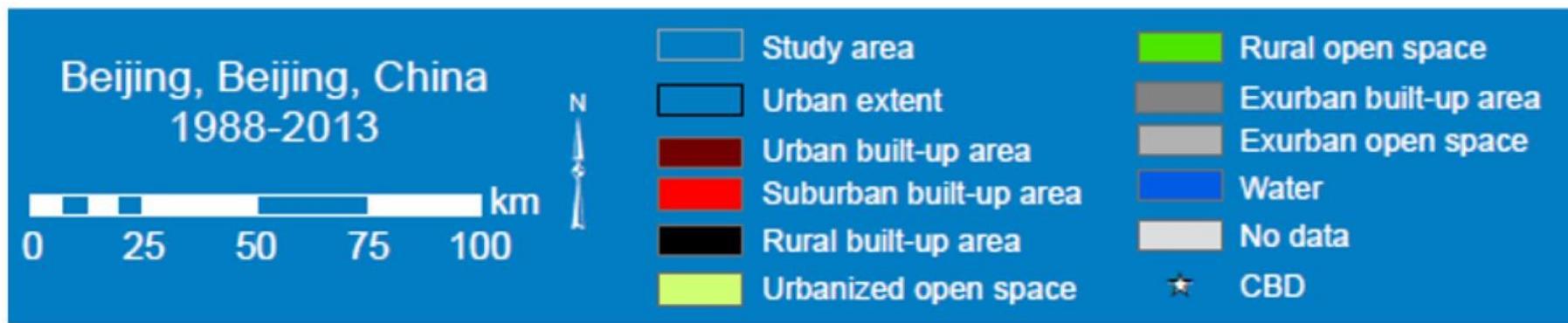
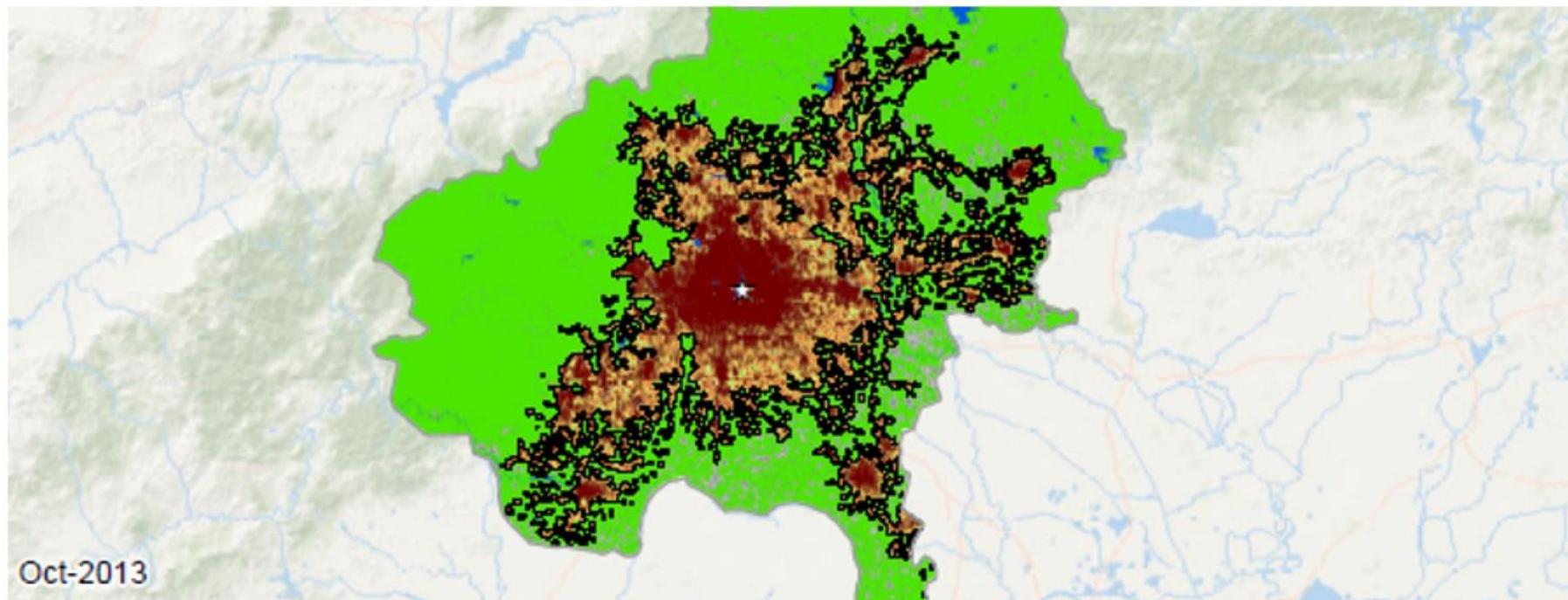


案例1：城市化的 水泥和钢铁依赖

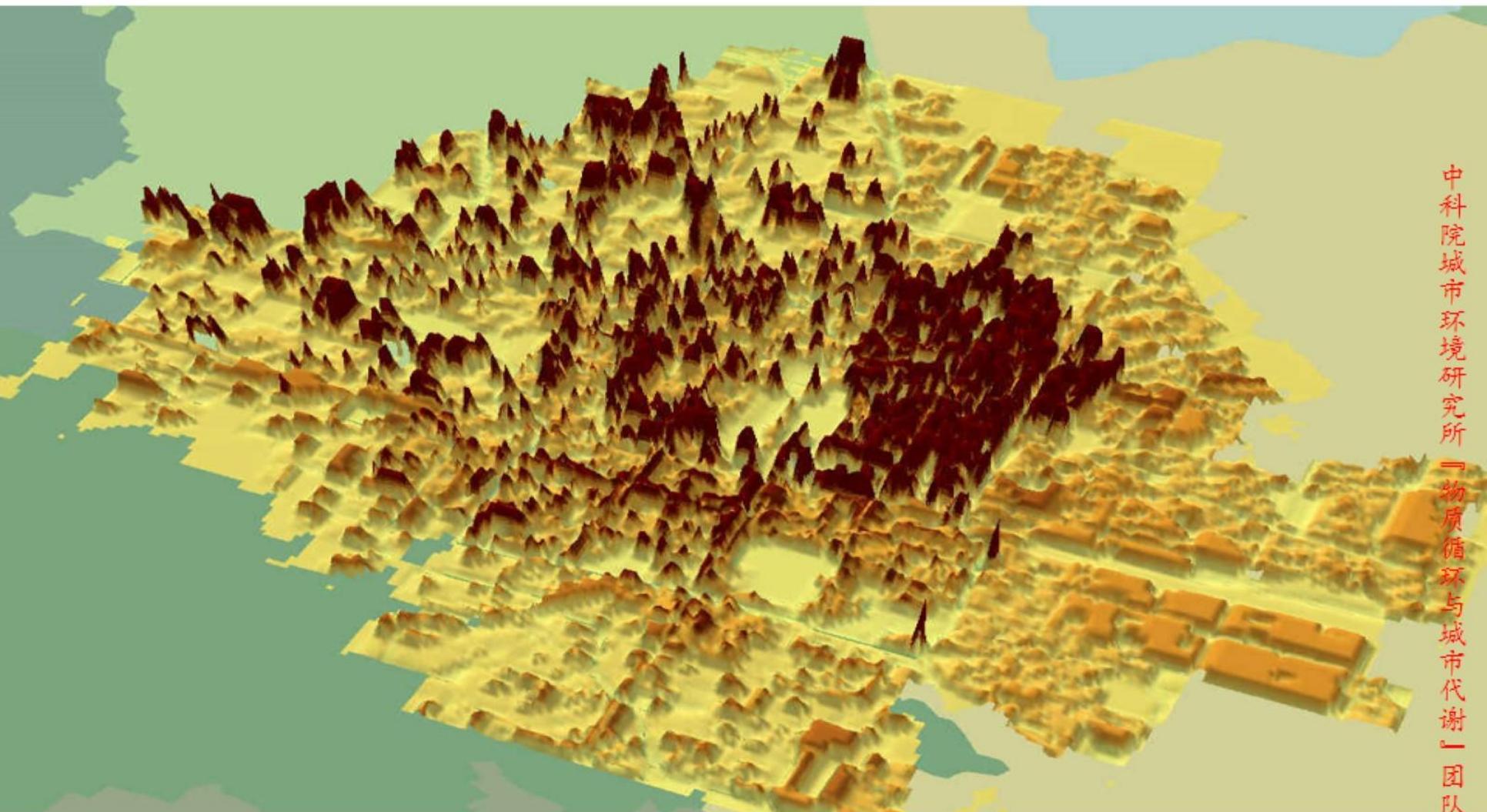
城市化研究的人口视角



城市化研究的土地视角

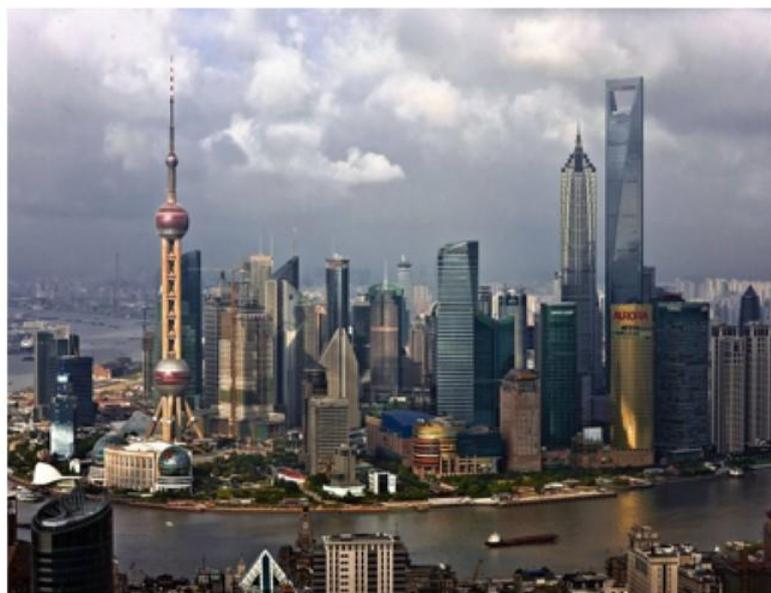


北京城的水泥和钢铁依赖



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中美典型城市化形态对比

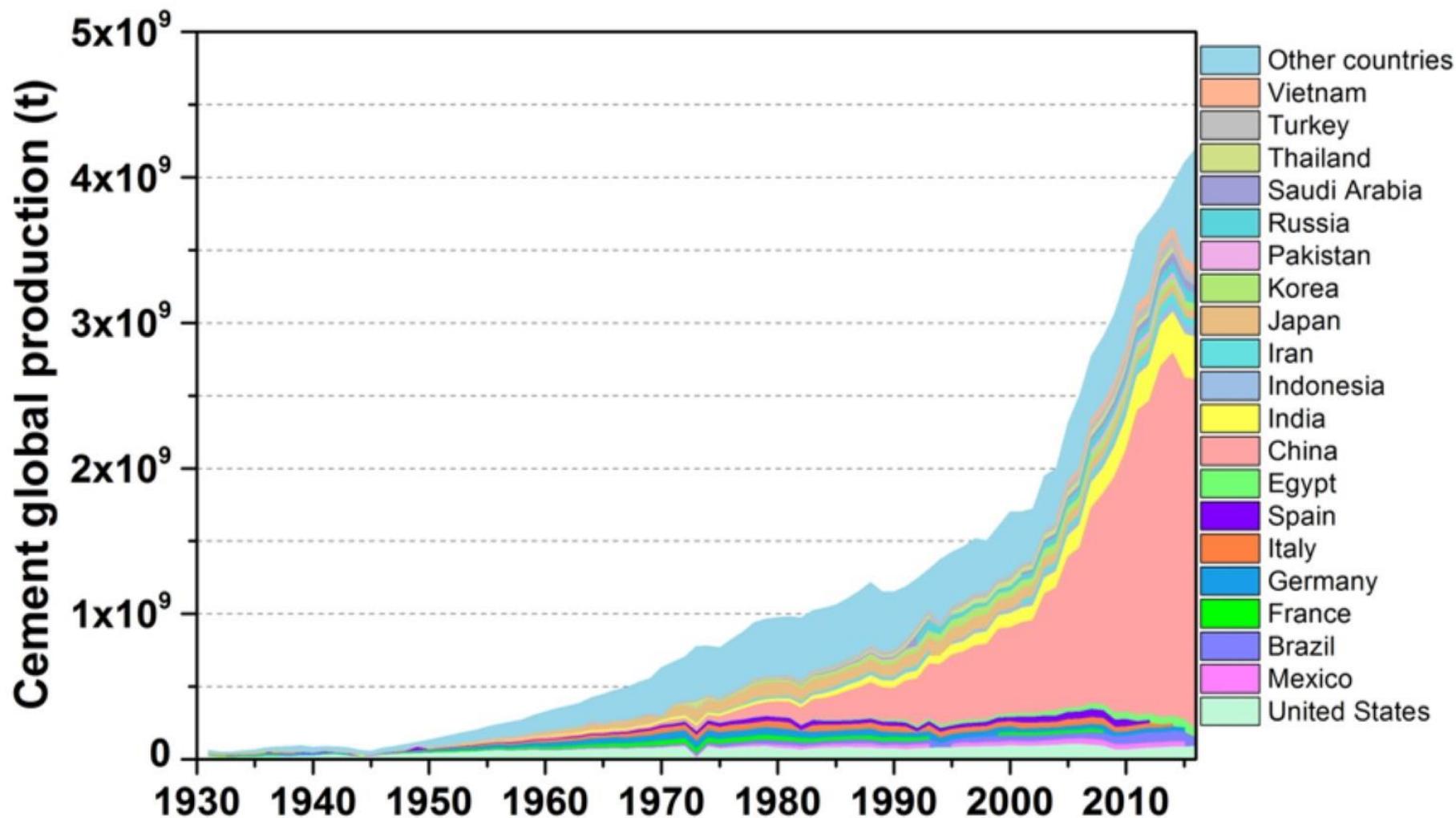


China, Shanghai



U.S., Phoenix

水泥生产的全球分布

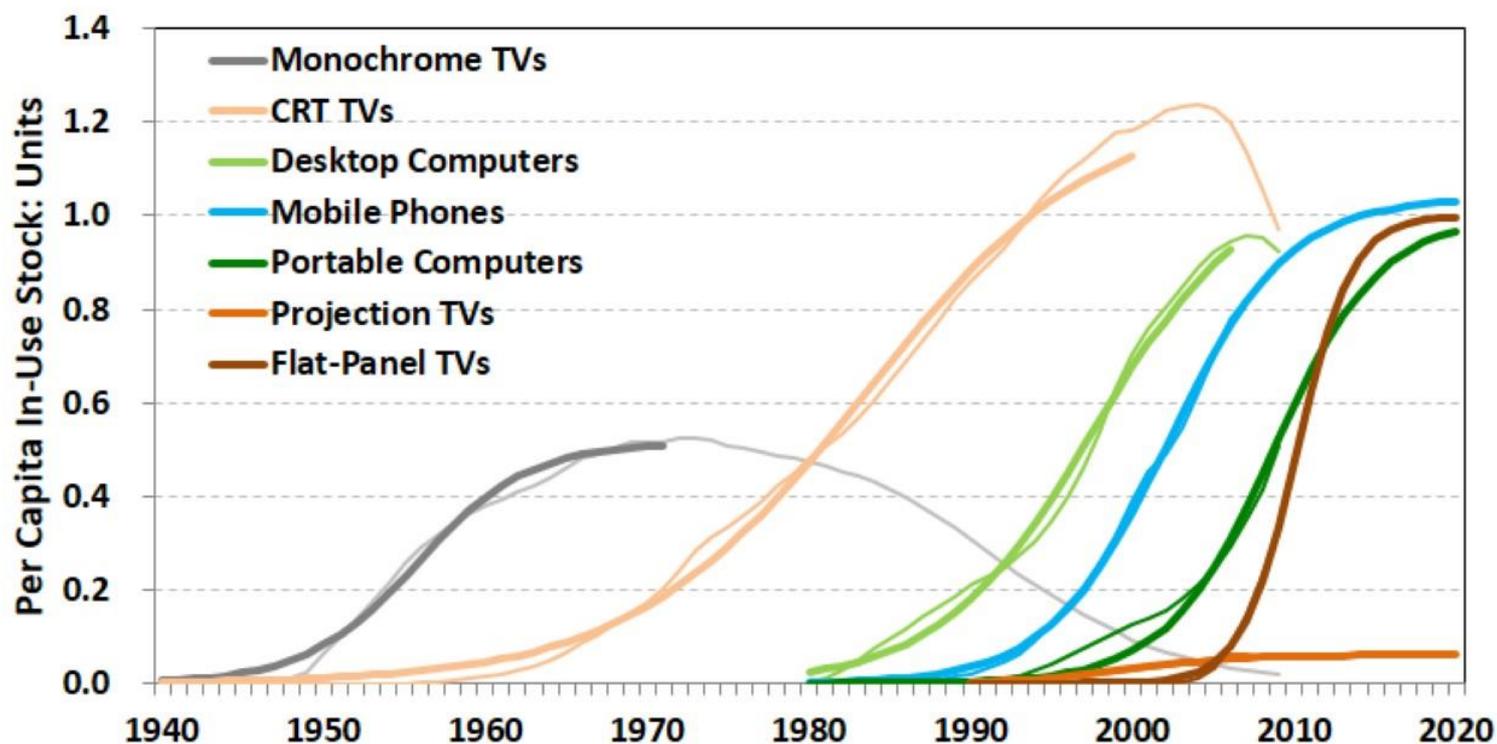


中科院城市环境研究所「物质循环与城市代谢」团队制作

来源：陈伟强课题组整理

案例2：电子产品的 “无所不用”

典型电子产品的演进



台式电脑的形态变化



1980s



泡泡网 PCPOP.COM

1990s



Let's Go Digital

2000s

来源：陈伟强课题组整理

电脑芯片的元素依赖

[1980s]

1 H 1.0079	2 He 4.0026											10 Ne 20.1797	11 Na 22.9897	12 Mg 24.3047											18 Ar 39.9481
3 Li 6.941	4 Be 9.0122											16 S 32.06	17 Cl 35.453	18 Ar 39.948											
19 K 39.0983	20 Ca 40.078	21 Sc 44.9559	22 Ti 47.867	23 V 50.942	24 Cr 51.9961	25 Mn 54.938	26 Fe 55.845	27 Co 58.9332	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.798								
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.6	53 I 126.905	54 Xe 131.29								
55 Cs 132.91	56 Ba 137.33	57-71 *	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.967	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)								
87 Fr (223)	88 Ra (226)	89-103 Ac																							

+4 Elements

[1990s]

1 H 1.0079	2 He 4.0026											10 Ne 20.1797	11 Na 22.9897	12 Mg 24.3047											18 Ar 39.9481
3 Li 6.941	4 Be 9.0122											16 S 32.06	17 Cl 35.453	18 Ar 39.948											
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87 Fr (223)	88 Ra (226)	89-103 Ac																							

+45 Elements
(Potential)

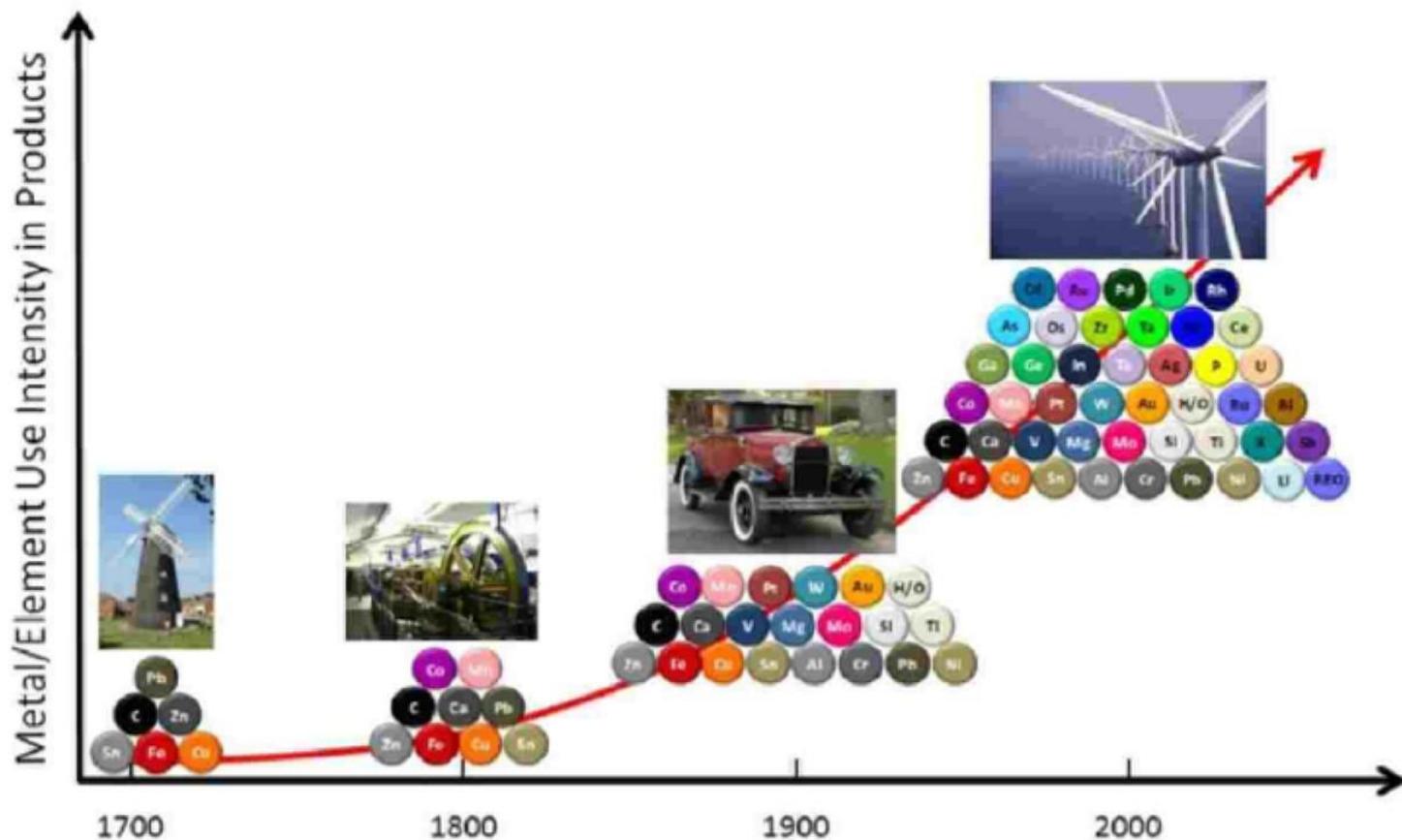
[2000s]

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87 Fr (223)	88 Ra (226)	89-103 Ac																							

11 Elements

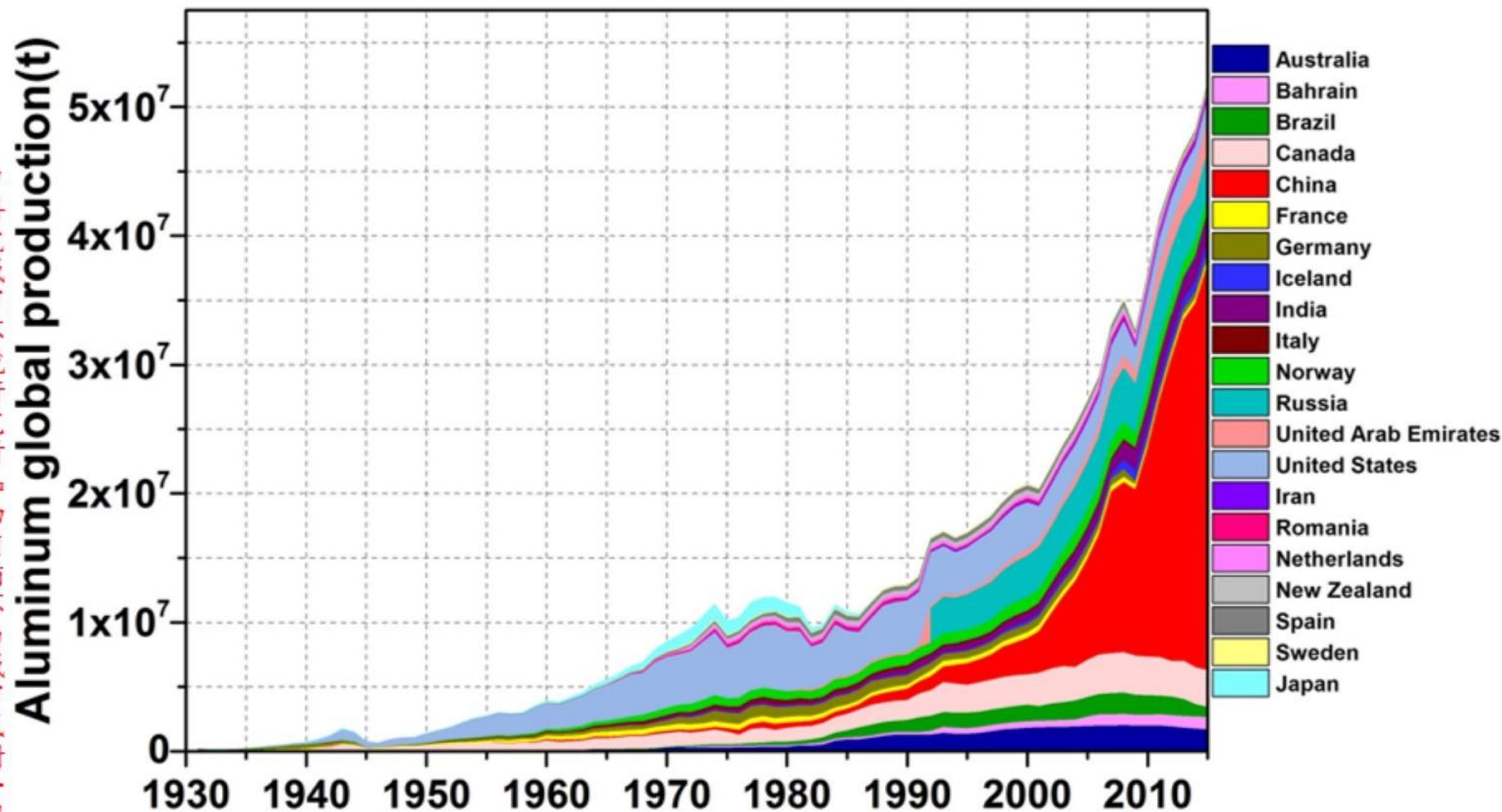
中科院城市环境研究所「物质循环与城市代谢」团队制作

材料使用的数量与复杂性增长



中科院城市环境研究所「物质循环与城市代谢」团队制作

我国金属生产和使用世界第一



中科院城市环境研究所「物质循环与城市代谢」团队制作

汇报提纲

- 人类世(时代)的物质循环
- 金属-能源关联 与 碳中和
- 研究团队与工作基础简介

NEXUS or LINKAGES

From Strüngmann Forum Reports

Linkages of Sustainability

Edited by Thomas E. Graedel and Ester van der Voet

Experts discuss the multiple components of sustainability, the constraints imposed by their linkages, and the necessity of taking a comprehensive view.

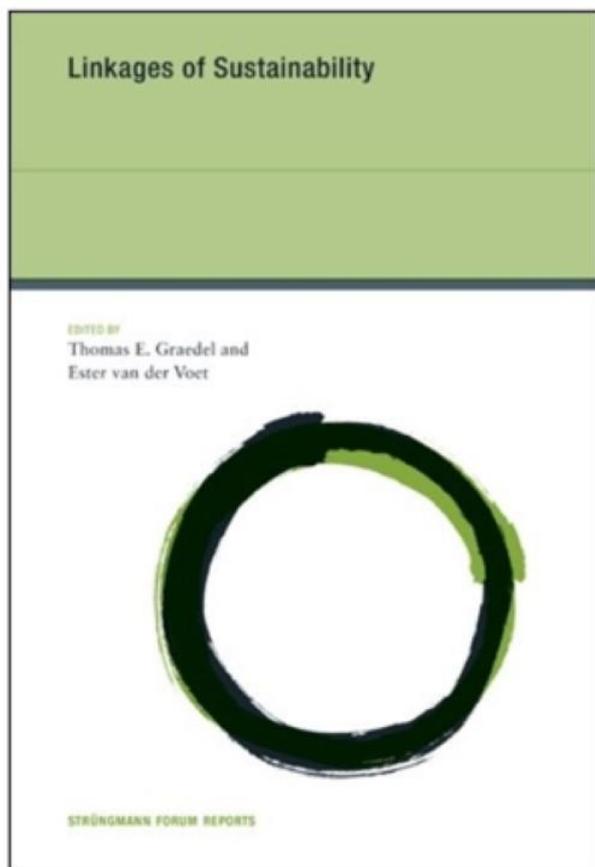


Tom Graedel

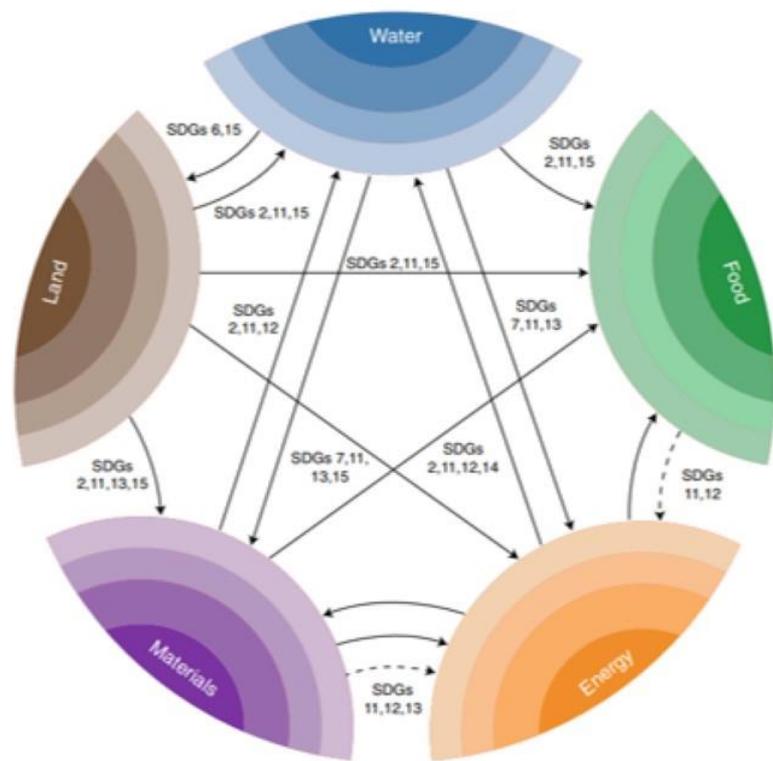
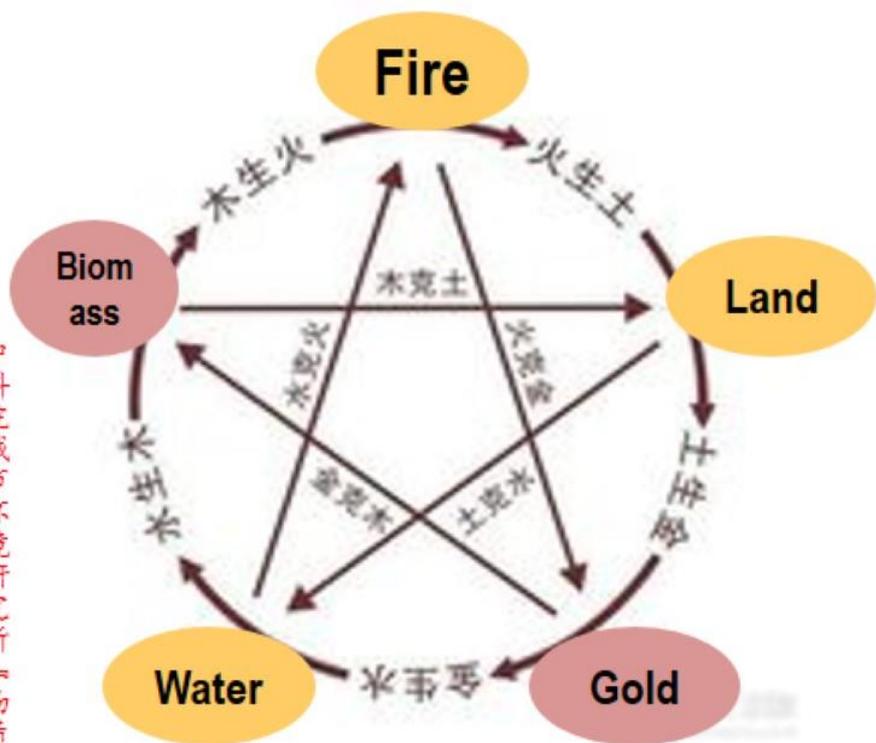
耶鲁大学教授

美国工程院院士

NRC关键矿产研究组成员



五行相生相克→可持续要素关联



五行相生相克：朴素思想，缺乏定量与科学论证
可持续要素关联：现代版五行，可定量和可扩展

要素关联：可持续发展的系统科学



面向可持续发展的资源关联研究：现状与展望

张超¹, 刘伟强², 李楠³, 汪鹏³, 陈伟强⁵, 张力⁶, 刘俊国⁷ 及 吕永龙⁸

Citation: [科学通报](#); doi: 10.1360/TB-2020-1193

View online: <https://engine.scichina.com/doi/10.1360/TB-2020-1193>

资源科学 2021, 43(4): 609-610
Resources Science 2021, 43(4): 609-610

引用格式: 张超, 王旭彪, 韩茹茹, 等. 全球关键金属-低碳能源关联研究综述及其启示[J]. 资源科学, 2021, 43(4): 609-610.
[Wang P, Wang Q C, Han R R, et al. Nexus between low-carbon energy and critical metals: Literature review and implications[J]. Resources Science, 2021, 43(4): 609-610.] DOI: 10.1360/TB-2020-1193

全球关键金属-低碳能源关联研究综述及其启示

汪 鹏¹, 王旭彪¹, 韩茹茹², 汤林彬^{1,3}, 刘 呈¹, 蔡阔佳^{1,4}, 陈伟强^{1,5}

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摘 要: 在“碳中和”背景下, 学术界日益清醒地认识到“关键金属”与低碳能源需求之间存在紧密的相互依赖关系。为提升国际社会对“关键金属-低碳能源”关联研究的认识, 本文整理了该领域2000—2020年发表的200多篇文献资料, 总结了该领域研究的发展历程与最新进展, 阐述了主要的科学发现: ①能源供给转型驱动多种关键金属的开采量和贸易量快速增长, 加剧关键金属供应区域的生态和环境压力; ②能源世界各区域对关键金属需求的结构和分布; ③部分关键金属存在储量不足、贸易供应脆弱、地理分布不均、环境污染严重风险, 并期待全球能源转型产生的清洁能源全球资源分配不均; ④中国作为多种关键金属的生产、消费和贸易大国, 为提升全球能源转型带来的清洁能源和低碳能源, 且自身同时面临关键金属供应脆弱风险, 建议在“碳达峰”与“碳中和”目标背景下, 中国应优先发展清洁能源关联研究, 开展金属-能源协同管理, 研判关键金属对中国发展低碳技术的支撑和限制作用, 警惕能源系统低碳转型带来的新型地缘政治风险。

关键词: 低碳能源; 关键矿产; 金属-能源关联; 环境影响; 资源安全供应



可持续发展目标内容：

- 2-零饥饿
- 6-清洁饮水和卫生设施
- 7-经济实用的清洁能源
- 9-产业、创新和基础设施
- 11-可持续城市和社区
- 12-负责任消费和生产
- 13-气候行动
- 14-水下生物
- 15-陆地生物

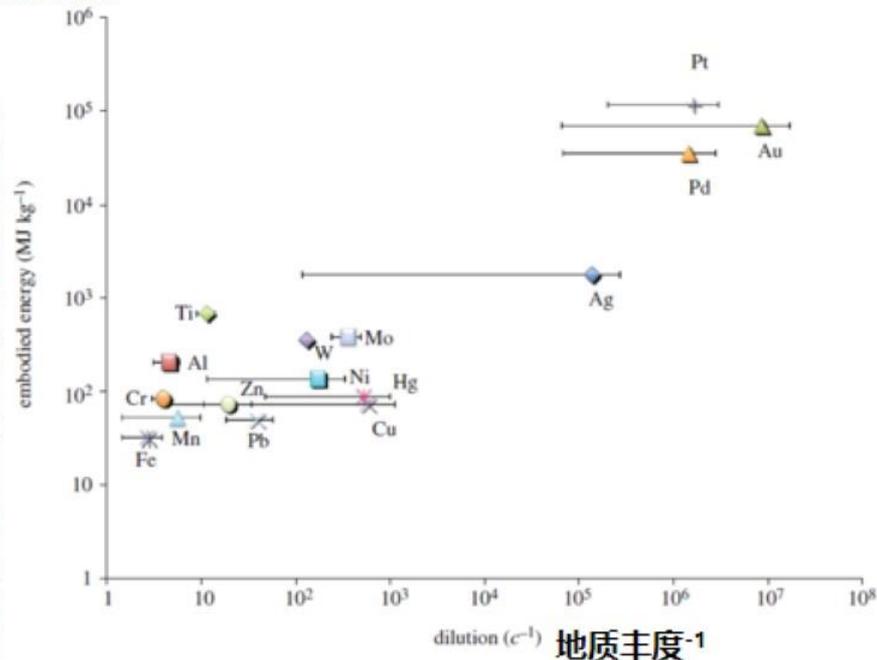
← 依赖关系
← - - 替代关系

推进“碳中和”目标需要考虑能源与多要素关联
重点：金属-能源关联

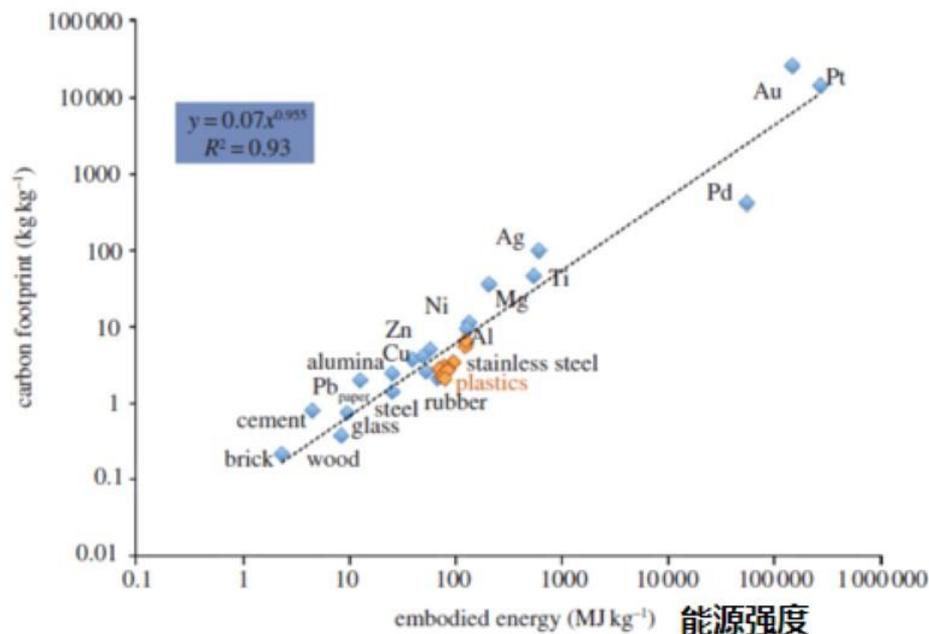
要点一： 没有能源，则没有金属

金属-能源-碳排放是交叉“复合体”

能源强度



碳排放强度



金属作为“耗能资源”：所有金属采、选、冶都需要能源

中科院城市环境研究所「物质循环与城市代谢」团队制作

钢铁工业“碳中和”亟需生产和消费协同变革



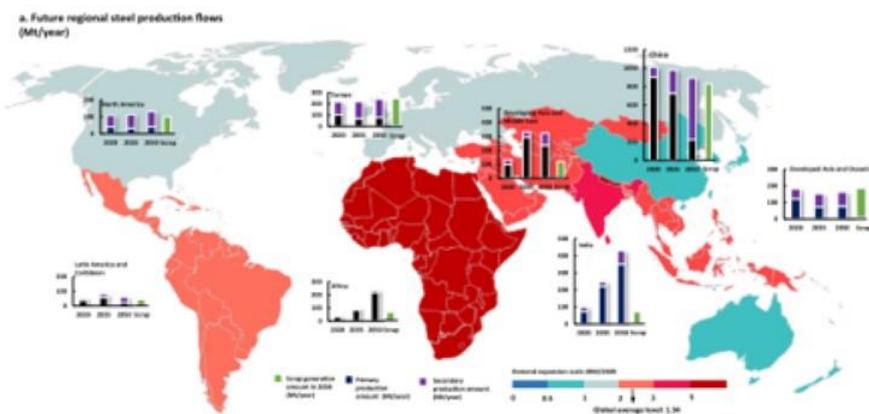
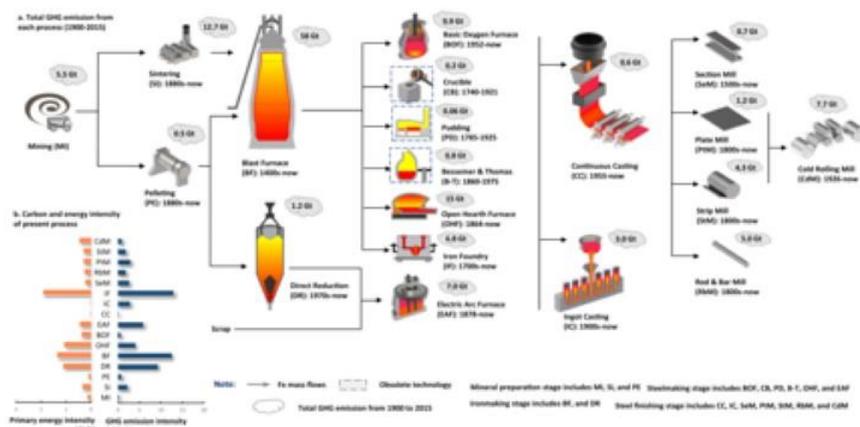
ARTICLE

<https://doi.org/10.1038/s41467-021-22245-6> OPEN

Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts

Peng Wang^{1,2}, Morten Ryberg^{3,4,5}, Yi Yang^{1,4,5}, Kuishuang Feng^{6,7}, Sami Kara^{8,9}, Michael Hauschild³ & Wei-Qiang Chen^{1,8,10}

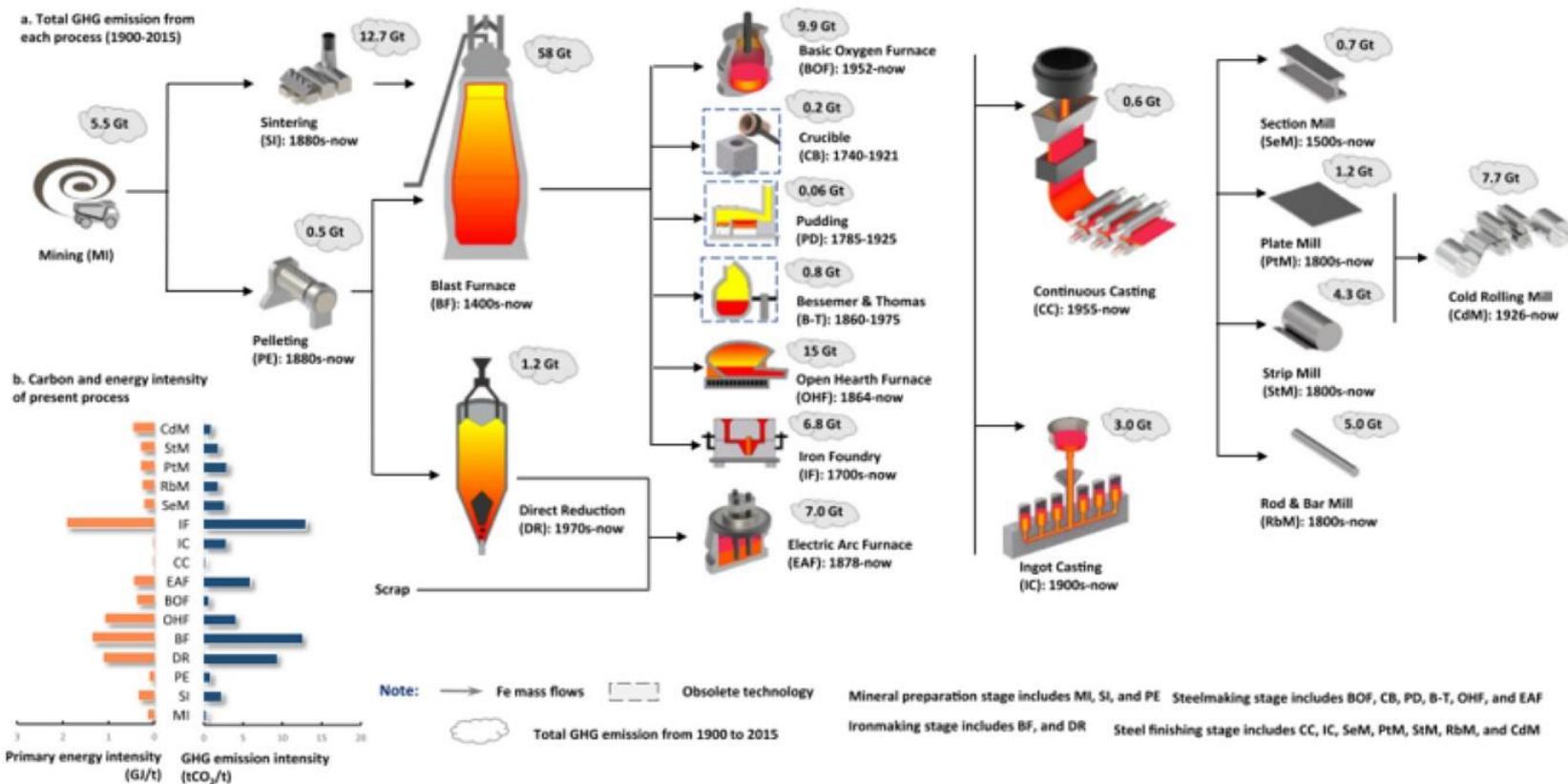
Steel production is a difficult-to-mitigate sector that challenges climate mitigation commitments. Efforts for future decarbonization can benefit from understanding its progress to date. Here we report on greenhouse gas emissions from global steel production over the past century (1900–2015) by combining material flow analysis and life cycle assessment. We find that ~45 Gt steel was produced in this period leading to emissions of ~147 Gt CO₂-eq. Significant improvement in process efficiency (~67%) was achieved, but was offset by a 44-fold increase in annual steel production, resulting in a 17-fold net increase in annual emissions. Despite some regional technical improvements, the industry's decarbonization progress at the global scale has largely stagnated since 1995 mainly due to expanded production in emerging countries with high carbon intensity. Our analysis of future scenarios indicates that the expected demand expansion in these countries may jeopardize steel industry's prospects for following 1.5 °C emission reduction pathways. To achieve the Paris climate goals, there is an urgent need for rapid implementation of joint supply- and demand-side mitigation measures around the world in consideration of regional conditions.



解析钢铁冶炼工艺技术创新、物质代谢格局演变与温室气体排放增长之间的相互影响机制

中国科学院城市环境研究所「物质循环与城市代谢」团队制作

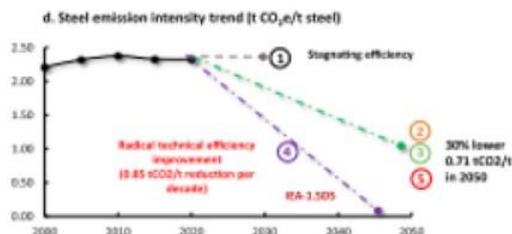
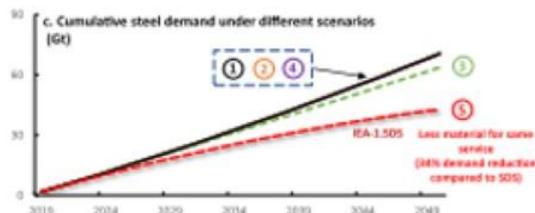
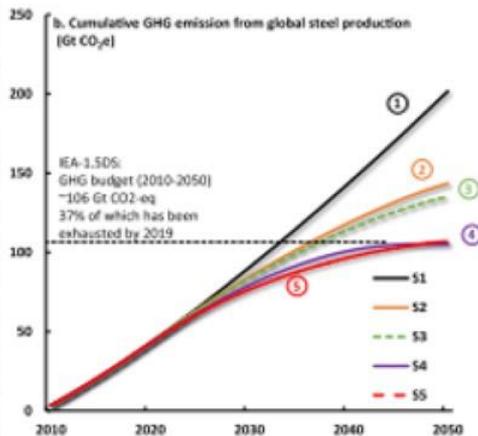
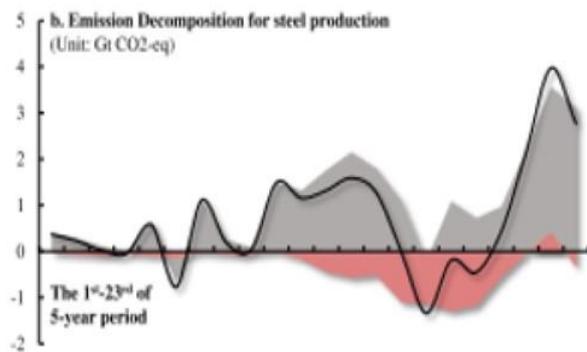
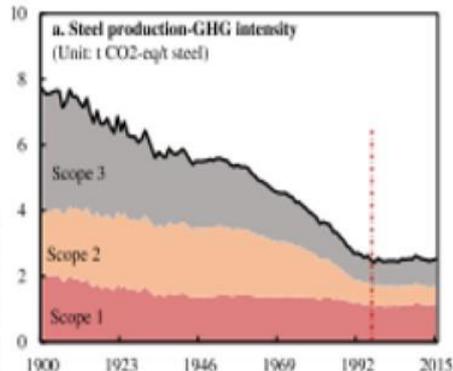
钢铁工业“碳中和”亟需生产和消费协同变革



钢铁脱碳极为艰难，主要受限于冶金原理、工艺和产能的三重约束

钢铁工业“碳中和”亟需生产和消费协同变革

中科院城市环境研究所「物质循环与城市代谢」团队制作



钢铁工业“碳中和”亟需生产和消费协同变革 | 《自然-通讯》

原创 Nature Portfolio Nature Portfolio 1周前

nature portfolio

钢铁是世界使用量最大、应用范围最广的金属资源，其生产流程具有碳排放量高、碳减排难度大、碳锁定效应明显等特征。作为全球关键基础原料部门，钢铁工业的“脱碳化”不仅对行业自身低碳发展至关重要，更关乎下游建筑、交通、能源等行业的碳减排乃至全球温控目标的实现。在当前世界各国协力推动“碳中和”的时代背景下，全球钢铁工业必须要革新发展理念，从产业历史变迁、工艺技术变革、能源结构改善、供需格局演变等多个维度，深入厘清钢铁工业的脱碳进展与障碍，充分研究钢铁工业“碳中和”的主要措施与实现路径，加快推进全球钢铁工业的碳达峰、碳中和进程。

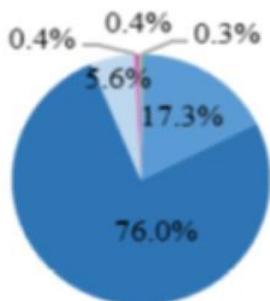
钢铁工业技术降碳效果遭遇“天花板”，其碳排放强度近三十年趋于停滞

全球钢铁工业需要在2047年左右全面实现碳中和，亟需推动生产和消费协同变革

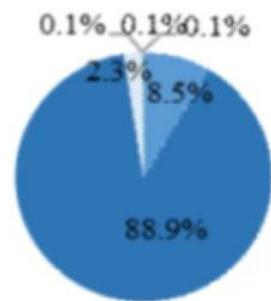
铝物质流过程中的能耗与碳排放



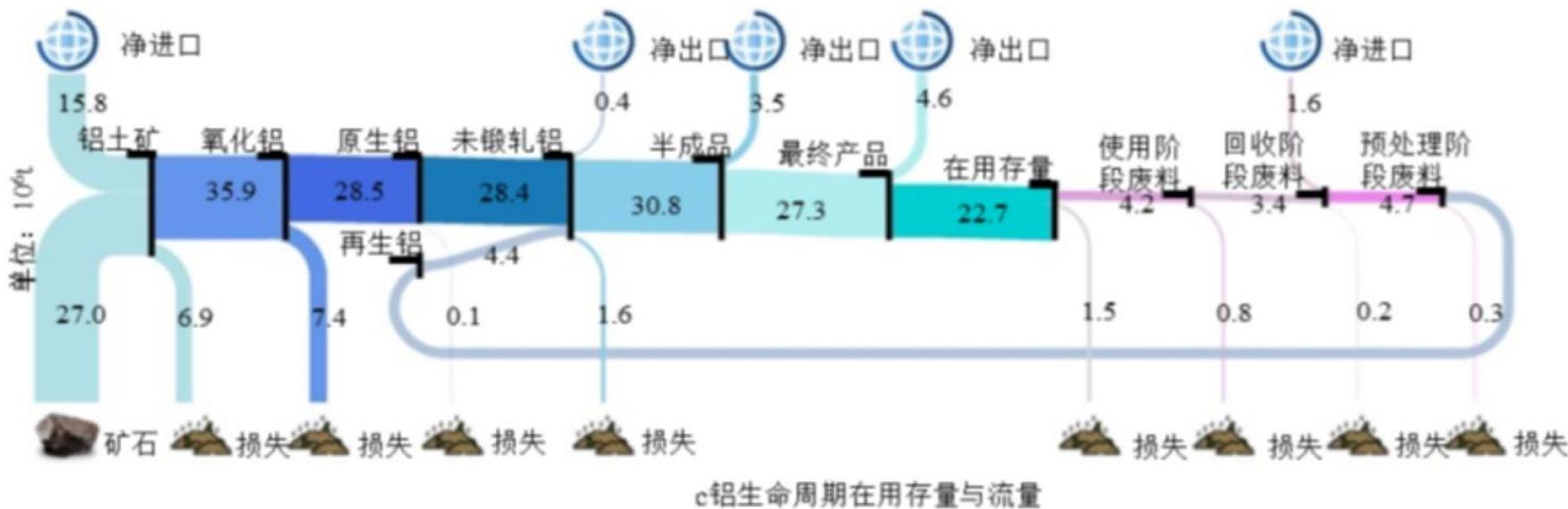
- 开采
- 冶炼
- 电解
- 加工
- 回收预处理
- 再熔铸



a 各阶段能耗占比



b 各阶段碳排放占比



铝工业“碳中和”两大举措：物质“双循环” + 能源“清洁化”

中科院城市环境研究所「物质循环与城市代谢」团队制作

卢浩洁, 等. 中国环境科学. 2021.

要点二： 没有金属，也没有能源

资源科学

第43卷 第4期 2021年4月

2021, 43 (4): 669-681

Resources Science

Vol.43, No.4 Apr., 2021

引用格式:汪鹏,王翹楚,韩茹茹,等.全球关键金属-低碳能源关联研究综述及其启示[J].资源科学,2021,43(4):669-681.
[Wang P, Wang Q C, Han R R, et al. Nexus between low-carbon energy and critical metals: Literature review and implications[J]. Resources Science, 2021, 43(4): 669-681.] DOI: 10.18402/resci.2021.04.03

全球关键金属-低碳能源关联研究综述及其启示

汪 鹏¹,王翹楚¹,韩茹茹²,汤林彬^{1,3},刘 昱¹,蔡阔佳^{3,4},陈伟强^{1,5}

(1. 中国科学院城市环境研究所,中科院城市环境与健康重点实验室,厦门361021;2. 北京科技大学能源与环境工程学院,北京100083;3. 清华大学地球系统科学系,北京100084;4. 清华-力拓资源能源与可持续发展研究中心,北京100084;5. 中国科学院大学,北京100049)

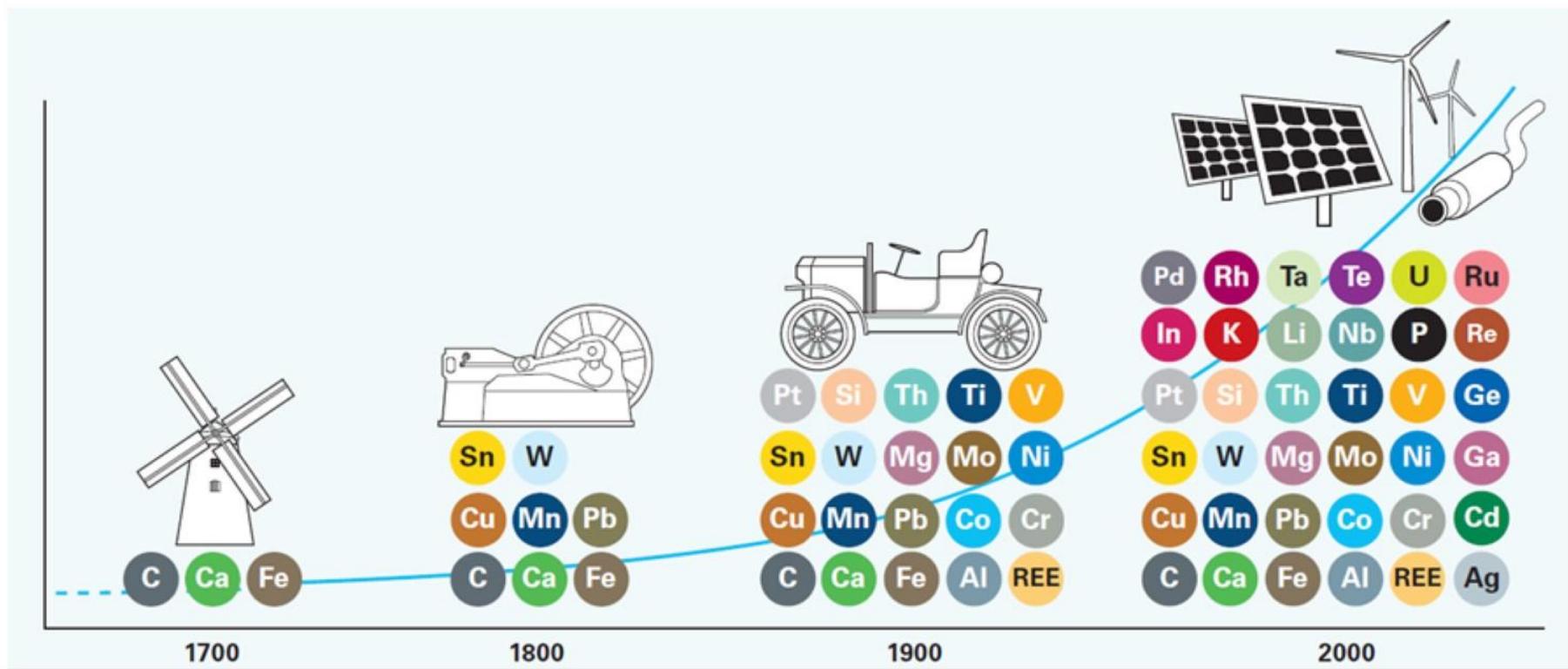
摘 要:在“碳中和”背景下,学术界日益清晰地认识到“关键金属”与低碳能源技术之间存在着紧密的相互依赖关系。为提升国际社会对“关键金属-低碳能源”关联研究的认识,本文整理了该领域2000—2020年发表的200多篇文献资料,综述了该领域研究的发展历程与最新进展,阐述了主要的科学发现:①能源低碳转型将驱动多种关键金属的开采量和贸易量持续快速增长,加剧关键金属供应国的生态环境风险,加深世界各国对关键金属资源的依赖和竞争;②部分关键金属存在储量不足、贸易供应链脆弱、地理分布不均、环境污染严重等风险,并将对全球低碳转型产生的负,进而重塑全球能源地缘政治格局;③中国作为多种关键金属的生产、消费和贸易大国,为推动全球能源低碳转型付出了巨大的资源和环境代价,且自身同样面临关键金属供应短缺的风险。建议在“碳达峰”与“碳中和”目标的背景下,中国应深化金属-能源关联研究,开展金属-能源协同管理,研判关键金属对中国发展低碳技术的支撑和限制作用,警惕能源系统低碳转型带来的新型地缘政治风险。

关键词:低碳能源;关键矿产;金属-能源关联;环境影响;资源安全供应

DOI:10.18402/resci.2021.04.03

能源的物质依赖：碳基→金属基

中科院城市环境研究所「物质循环与城市代谢」团队制作



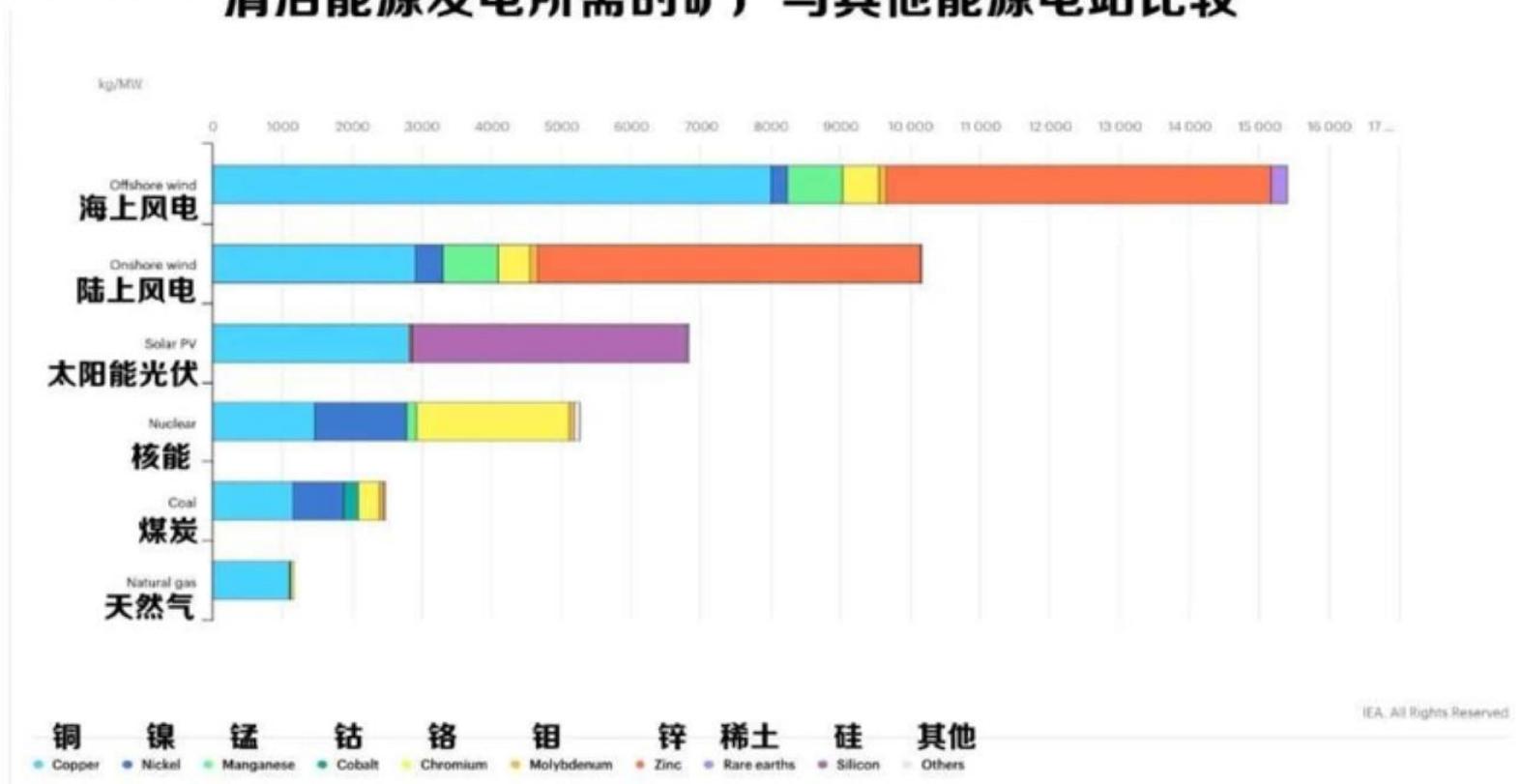
Modified based on BP (2014): Materials critical to the energy industry. An introduction. 2nd edition.

特征一：金属使用强度大

Minerals used in clean energy technologies compared to other power generation sources

Last updated 5 May 2021

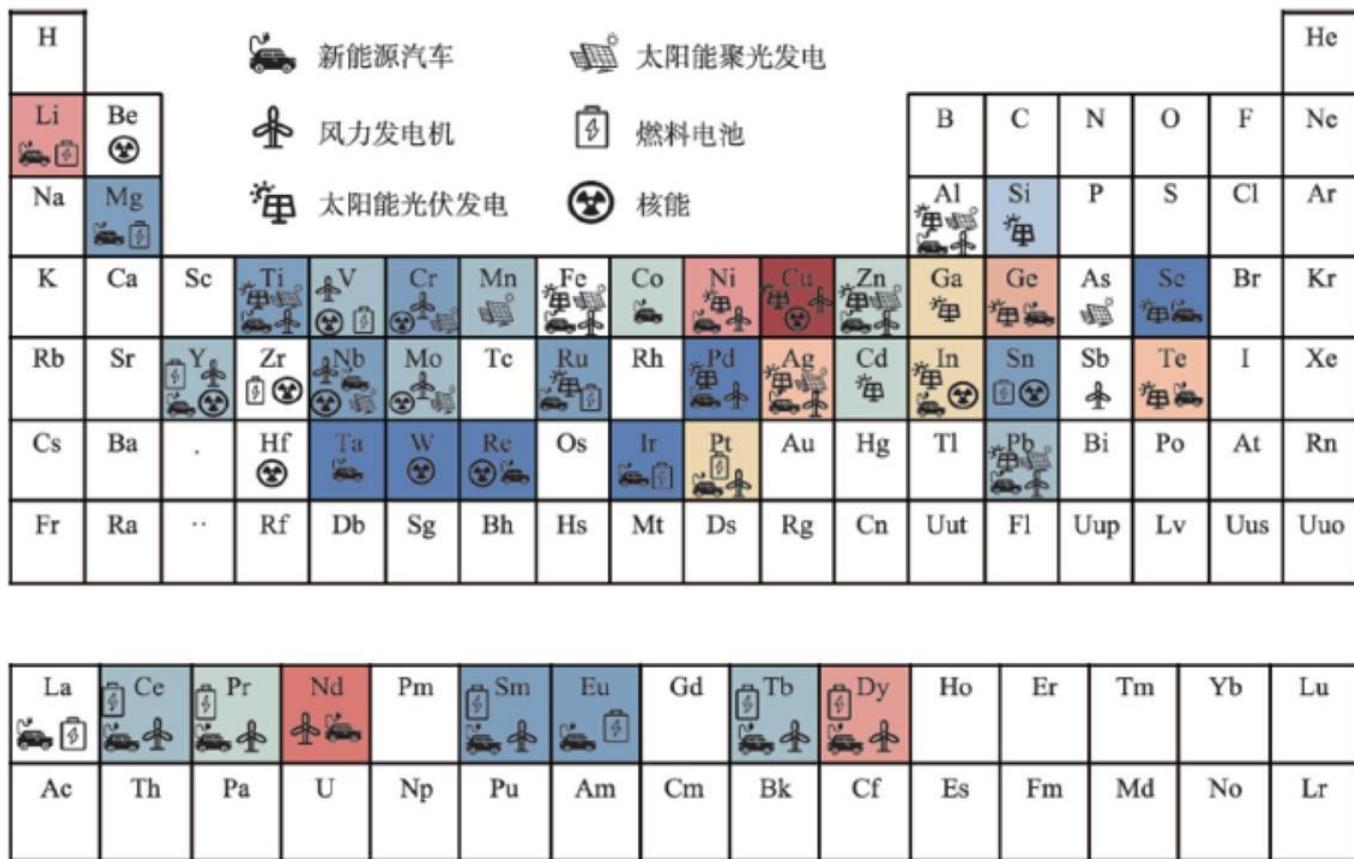
清洁能源发电所需的矿产与其他能源电站比较



特征二：金属使用种类多

	Wind	Solar photovoltaic	Concentrating solar power	Carbon capture and storage	Nuclear power	Light emitting diodes	Electric vehicles	Energy storage	Electric motors
Aluminium	X	X	X	X		X		X	X
Chromium	X			X	X	X			
Cobalt				X	X		X	X	
Copper	X	X		X	X	X	X		X
Indium		X		X	X	X			
Iron (cast)	X		X			X		X	
Iron (magnet)	X								X
Lead	X	X			X	X			
Manganese	X			X		X	X		
Molybdenum	X	X		X	X	X			
Neodymium (proxy for rare earths)	X						X		
Nickel	X	X		X	X	X	X	X	
Silver		X	X		X	X	X		
Steel (Engineering)	X								
Zinc		X				X			

特征三：金属使用对象广

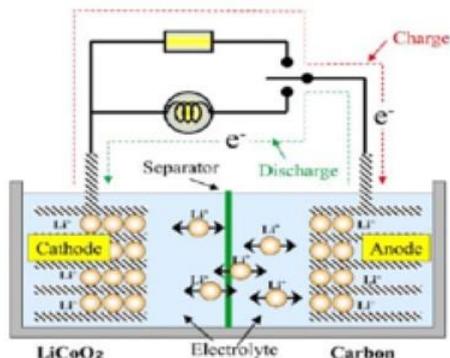


— “金”多“能”，相互竞争

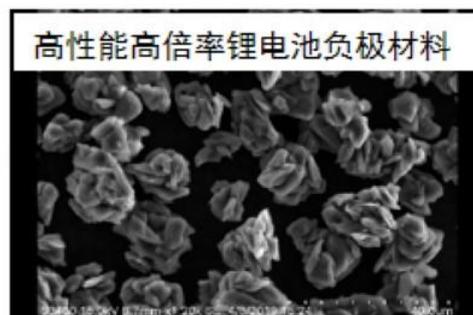


图3 关键金属与低碳技术的关联及关键金属受关注度

特征四：材料性能要求高

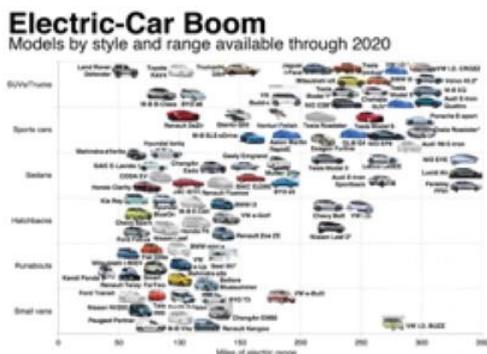


基础研究的“长期积累”



材料技术的“反复实验”

“金属高要求”



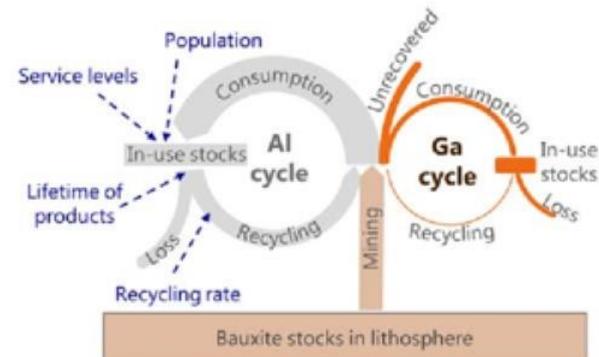
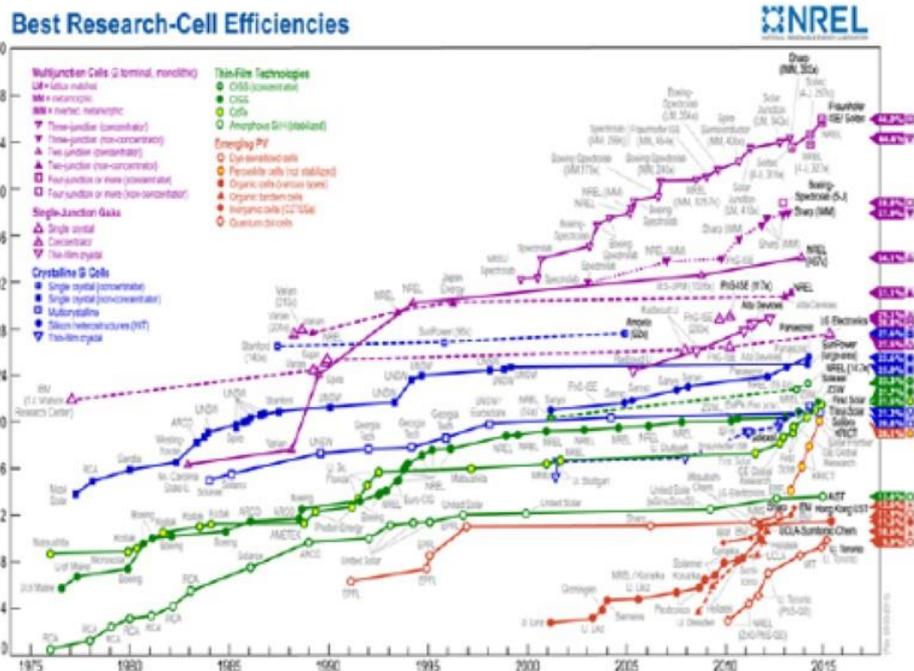
商品市场的“激烈竞争”



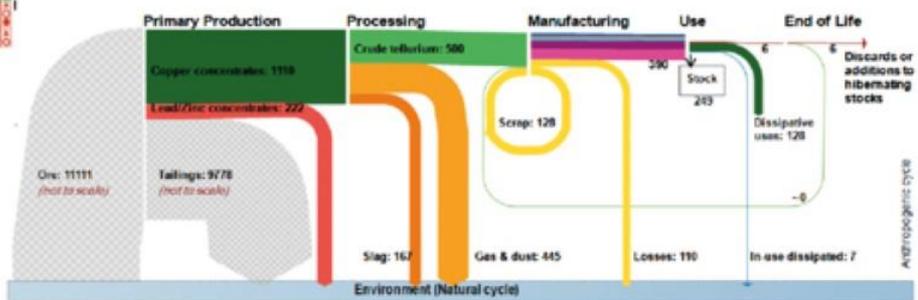
工业制造的“千锤百炼”

金属使用由传统大宗领域进入低碳能源领域

特征五：金属使用更新快



驱动镓金属循环(?)



光伏商用技术的种类与材料差异

- Iron and steel products
- Chemicals and catalysts
- Thermoelectric devices
- Tellurium products
- Additives to nonferrous alloys
- Rubber
- Photoreceptors
- Recycled Material

驱动碲循环(?)

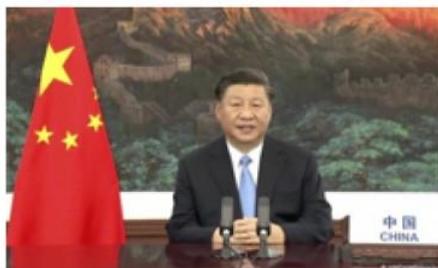
Amuned N. Løvrik et al., 2016; P Nuss et al., 2019

中科院城市环境研究所「物质循环与城市代谢」团队制作

来源：陈伟强课题组整理

要点三-金克火： 低碳能源转型的金属约束

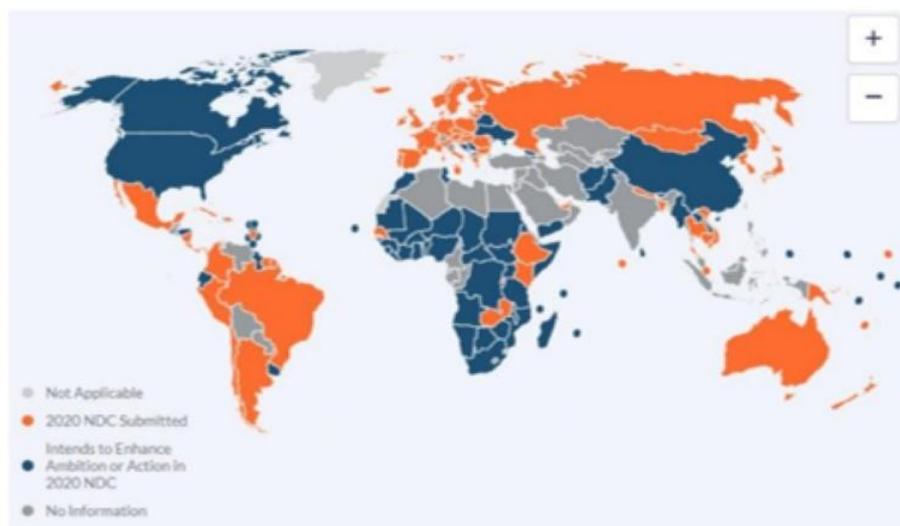
“碳中和”成为全球共同愿景



中国将提高国家自主贡献力度，采取更加有力的政策和措施，二氧化碳排放力争于2030年前达到峰值，努力争取2060年前实现碳中和。

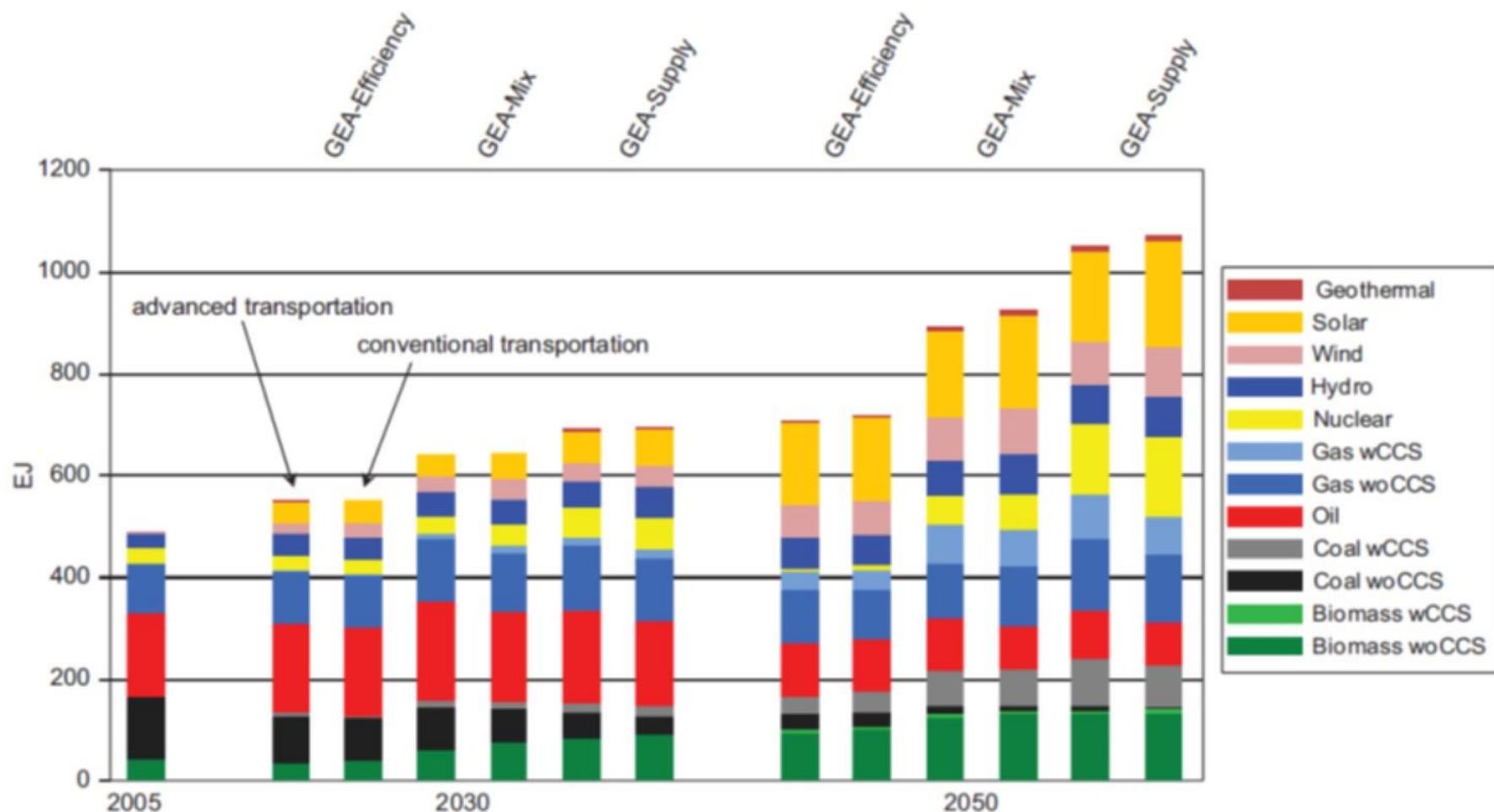
——习近平主席2020年9月联合国大会报告

碳中和得到**超过120多个**国家/地区积极响应



“碳中和”将促进世界能源和资源格局大发展和大变革

能源低碳发展是碳中和的核心举措



中科院城市环境研究所「物质循环与城市代谢」团队制作

低碳转型是大势所趋，但是

1. 低碳技术严重依赖战略金属

2. 能源无限，金属有限

3. 有些技术不一定真的低碳

4. 中国的贡献和环境代价被严重低估

“谁拥有金属，谁就拥有低碳能源”

发现1:

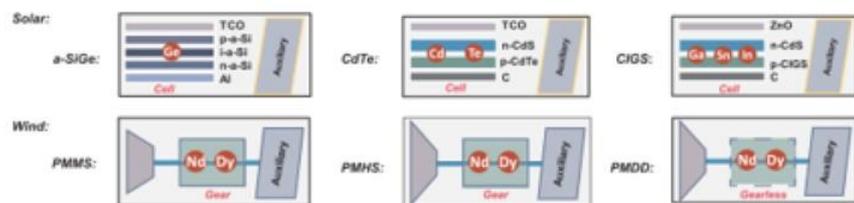
短期产能不足和长期
资源短缺均可能存在

年均需求量与产能对比

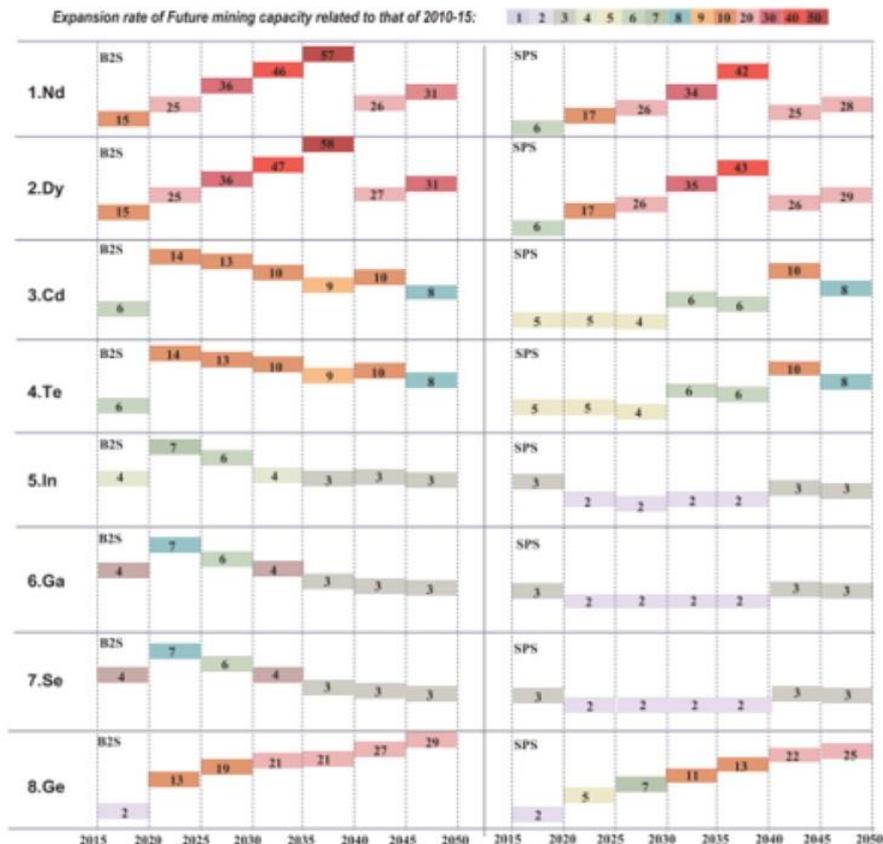
A: Life Cycle Framework



B: Technology and its critical metals



Expansion rate of Future mining capacity related to that of 2010-15:

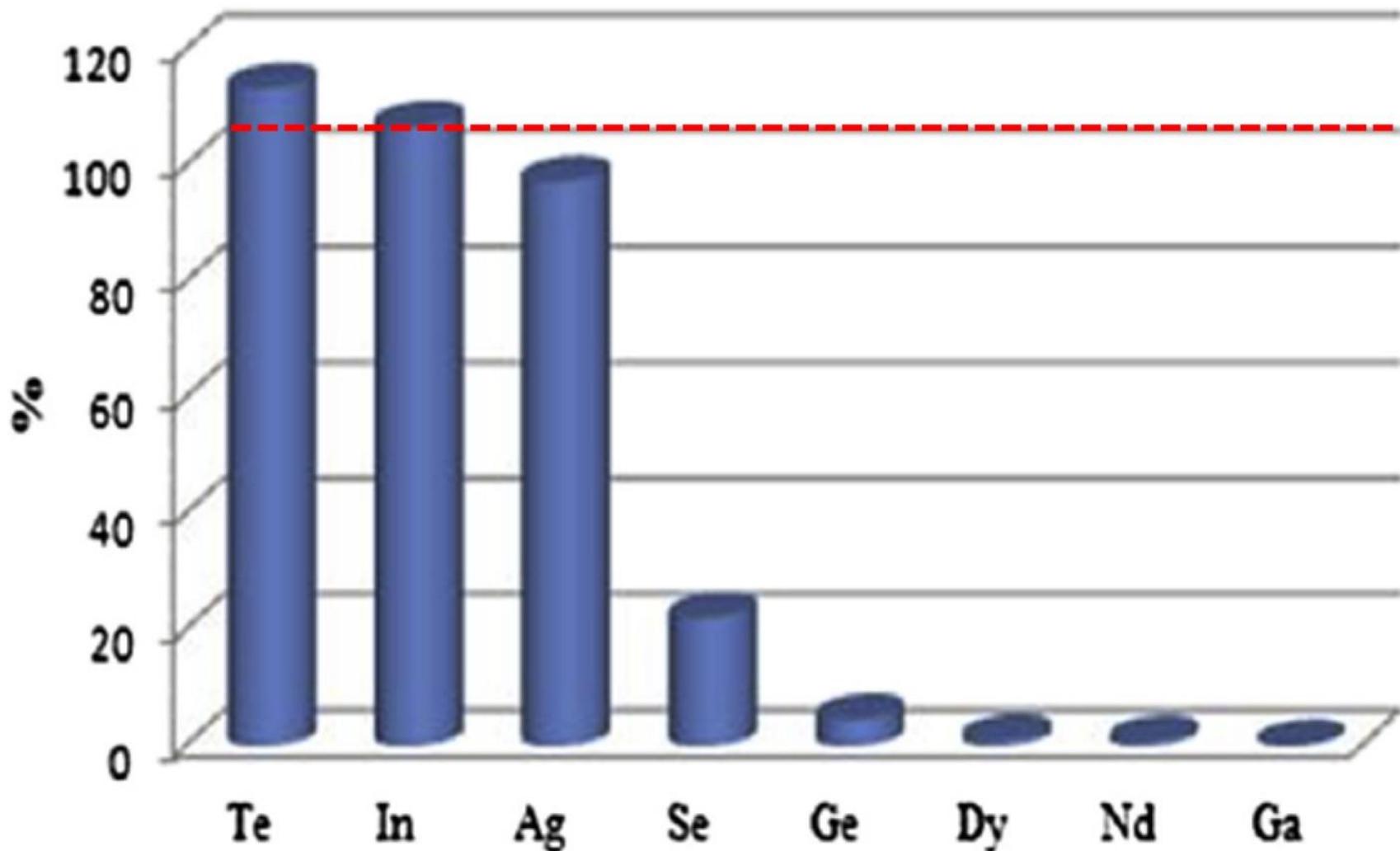


8类金属资源的需求增长趋势

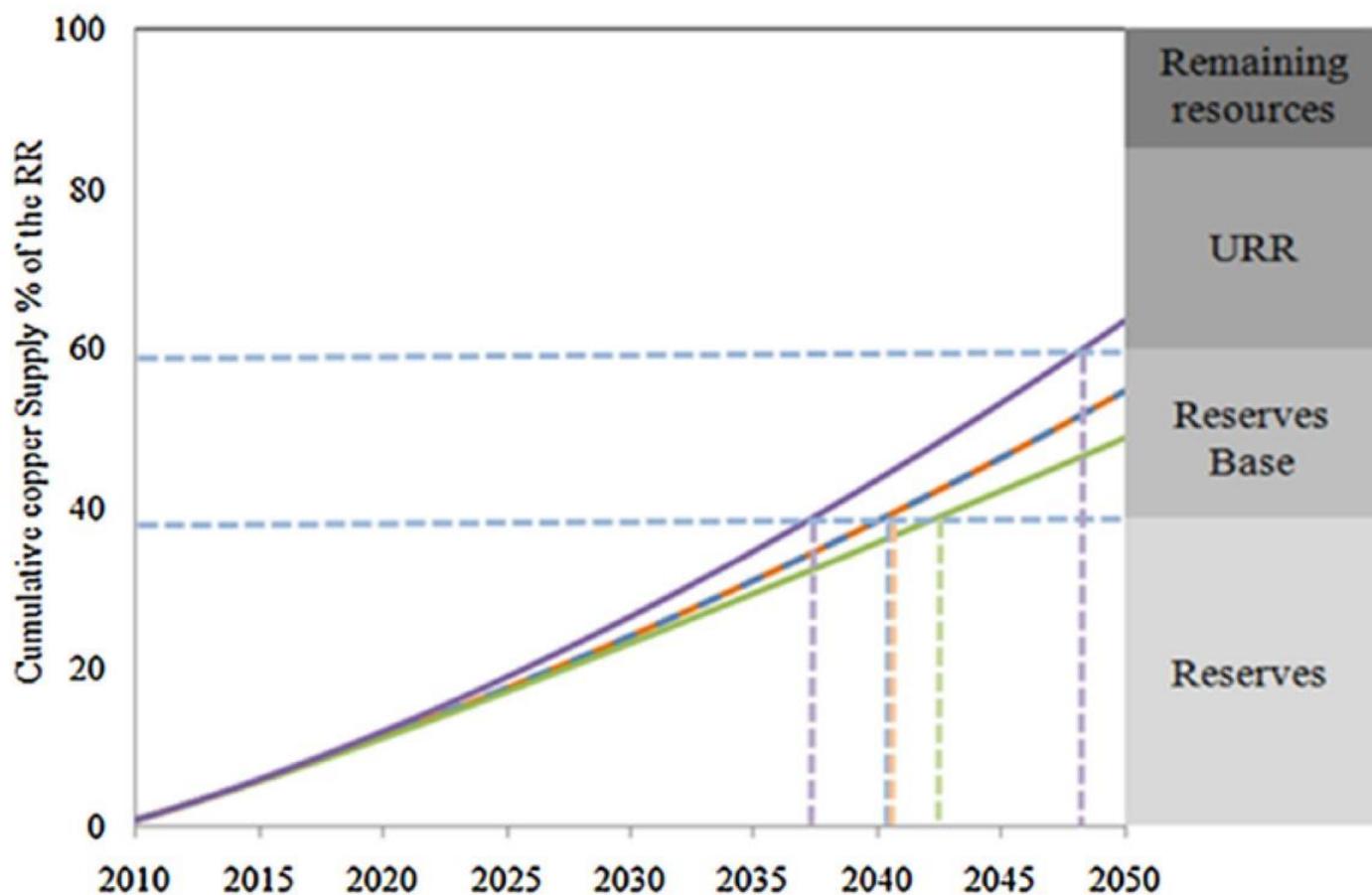
中科院城市环境研究所「物质循环与城市代谢」团队制作

中国碳中和目标下低碳发电技术情景分析

2016-2050累积需求量与储量对比



2050年可能面临的铜短缺

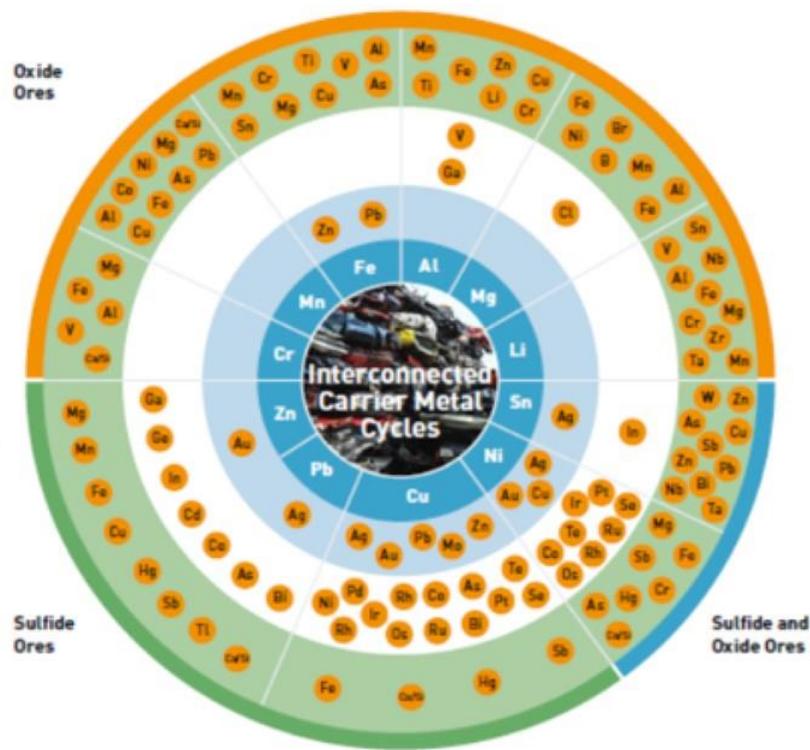
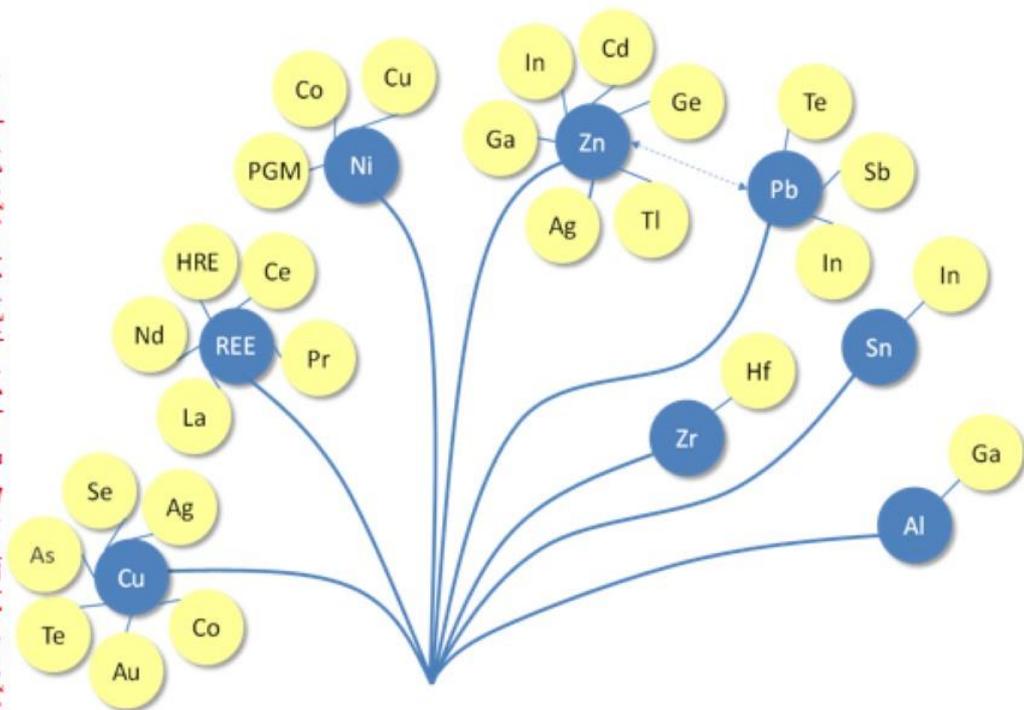


中科院城市环境研究所「物质循环与城市代谢」团队制作

发现2:

材料生产的能耗可能极大抵消低碳能源技术的减排效果

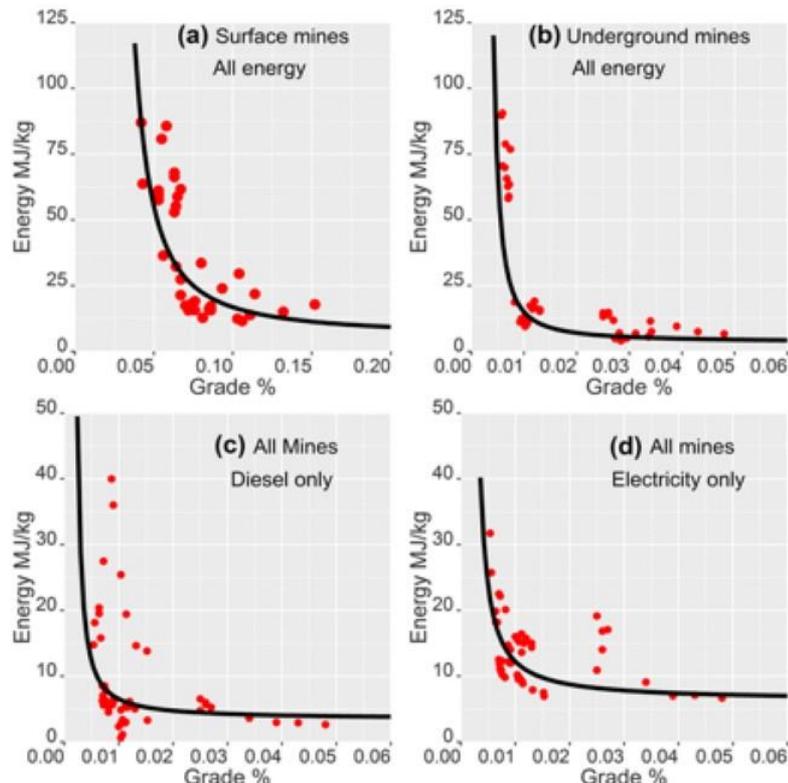
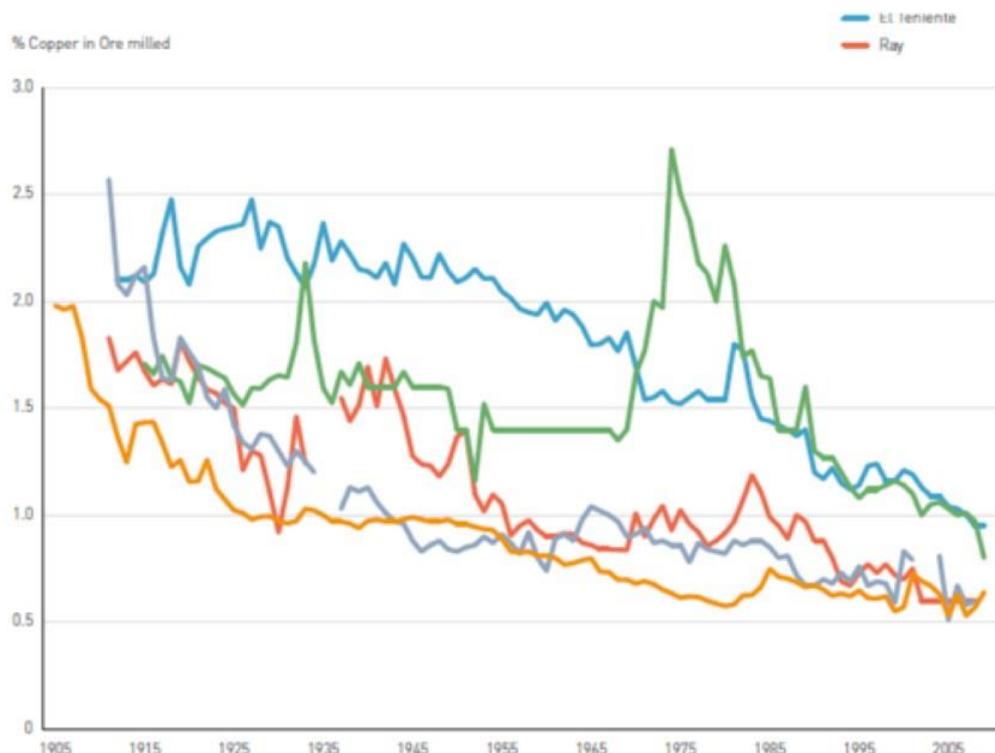
能源金属材料多以伴生形态存在



UNEP, 2013

© Yale University, 2009,
after Meskers and Hagelüken

能源金属矿产品位直线下降



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金属生产过程会产生多重污染

中科院城市环境研究所「物质循环与城市代谢」团队制作

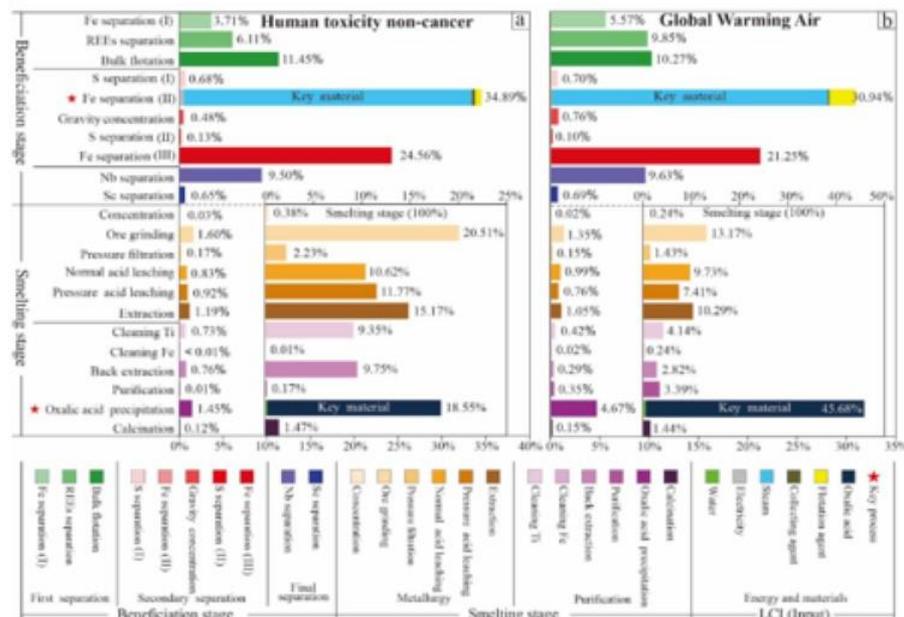
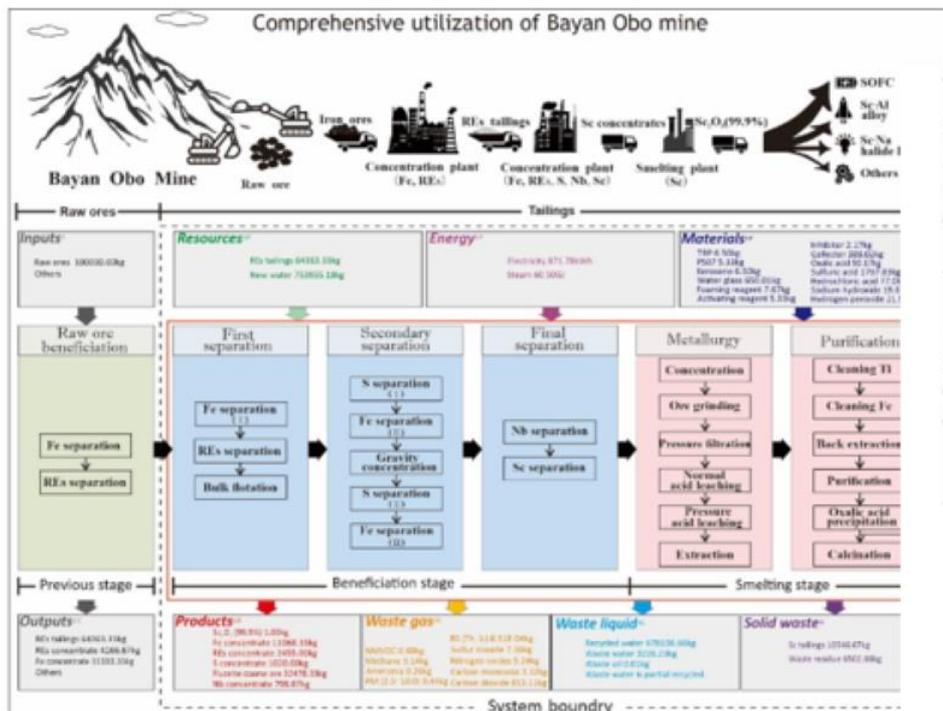
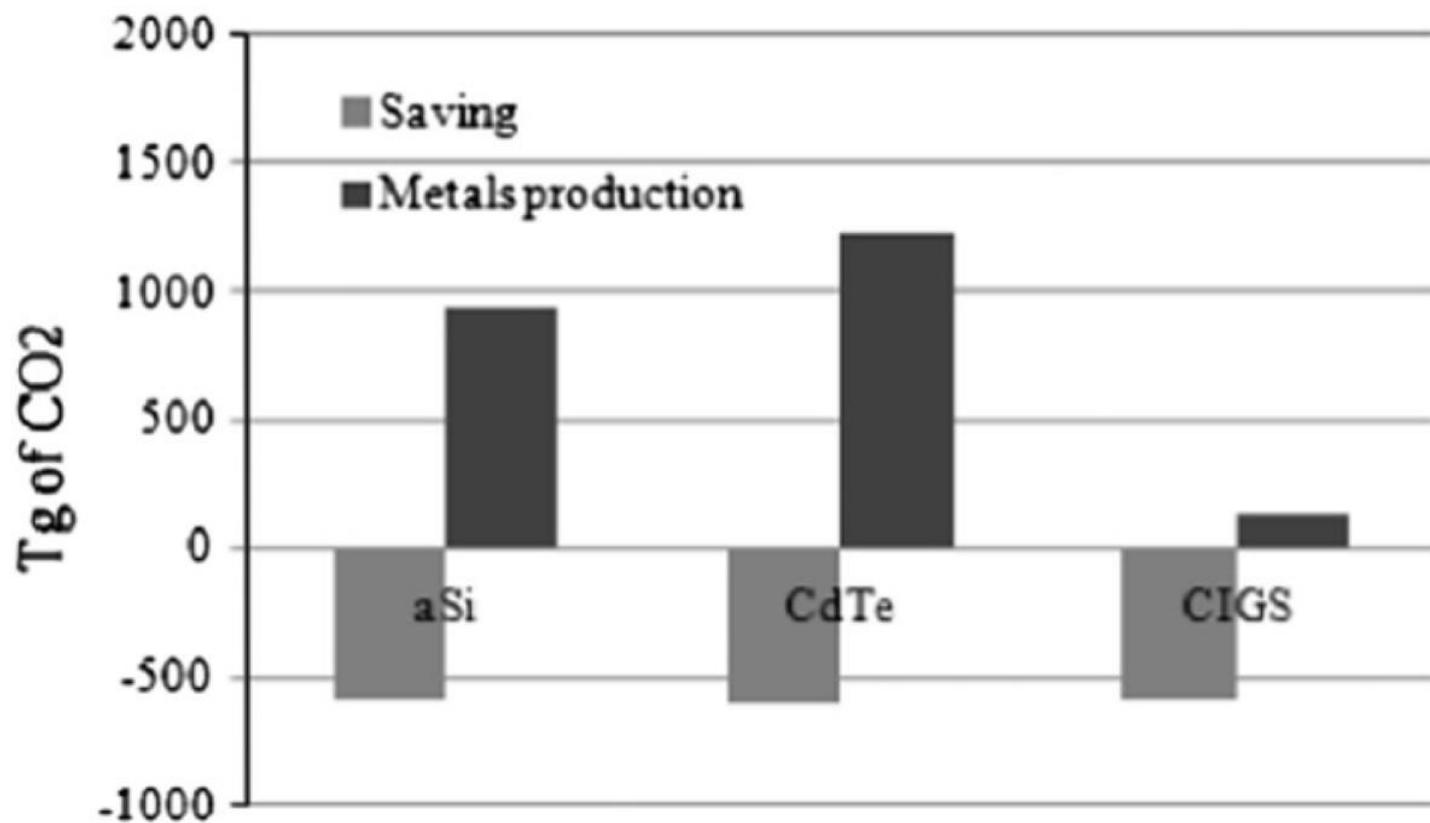


Fig. 4. Key process and material in the impact categories of HTNC and GWA.

材料生产抵消太阳能技术的减排效果

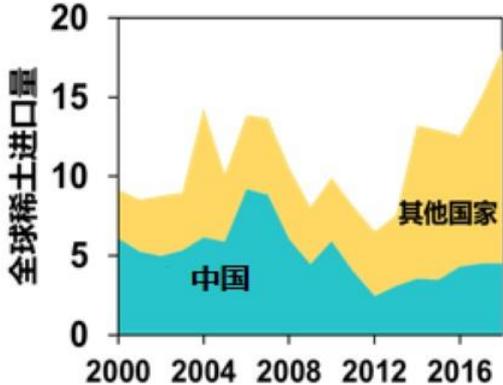
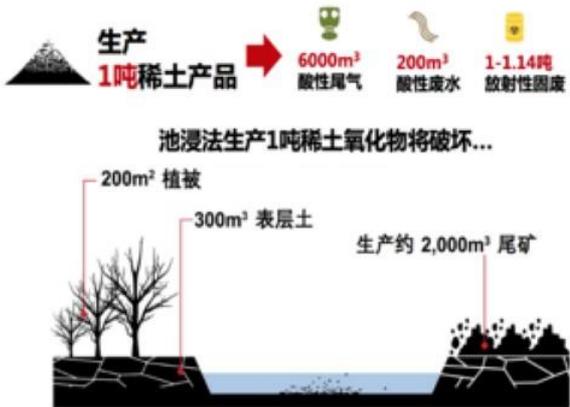


发现3:

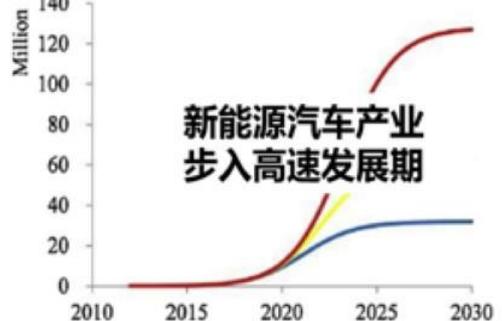
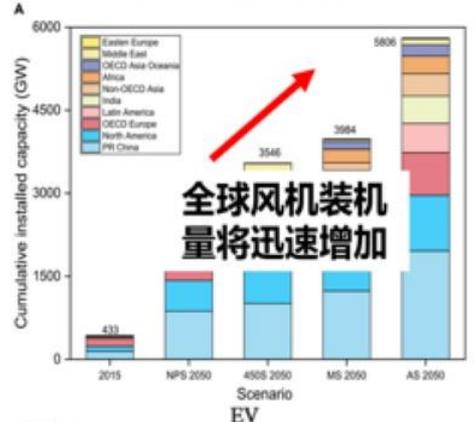
中国通过出口金属材料为世界的低碳转型作出巨大贡献

中国为世界承担环境代价+提供低碳减排能力

生产污染



消费清洁



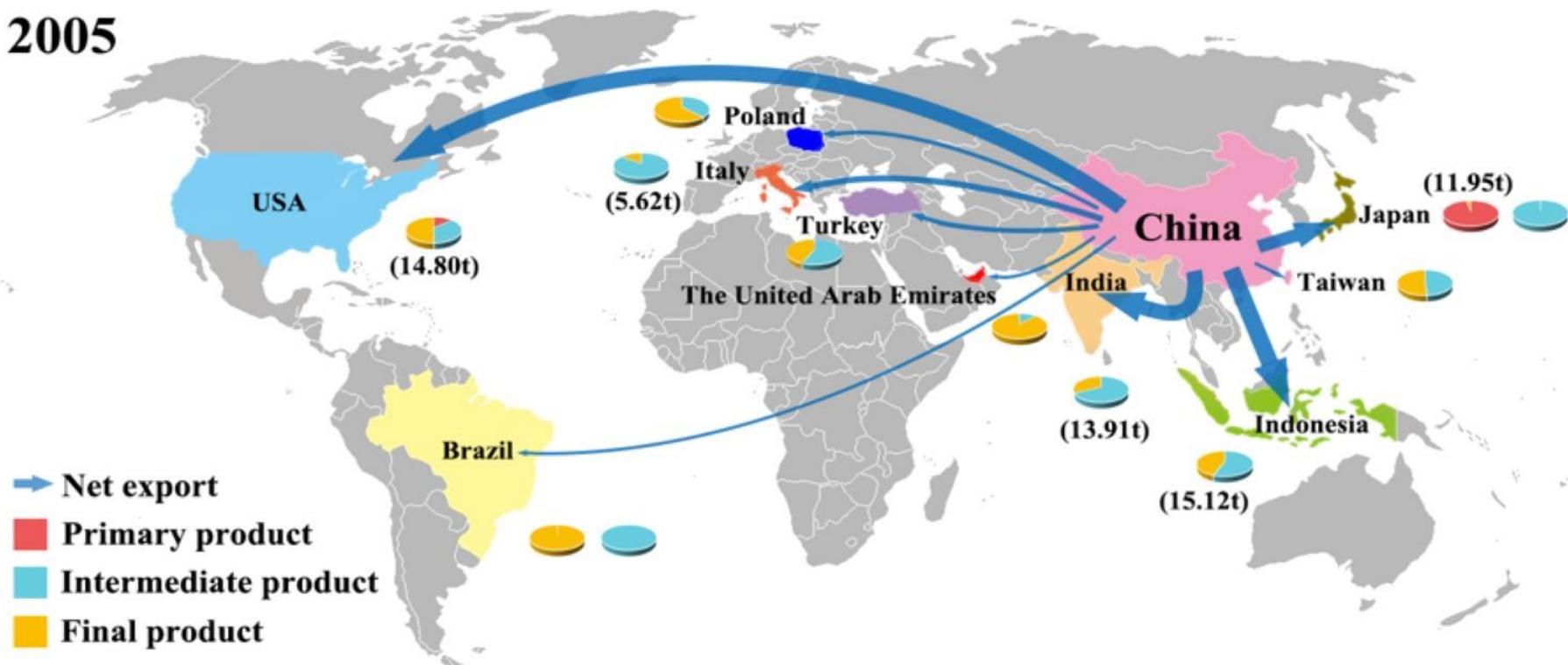
Source: L. Hayes-Labruzzo et al (2014), Rare earth pollution in Ganzhou, China Securities Journal, January 30, 2015
 Rare Earths Shades of Grey, China Water Risk 2016
 © China Water Risk 2016, all rights reserved

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资源去向：中国稀土钨出口去向和形态

2005

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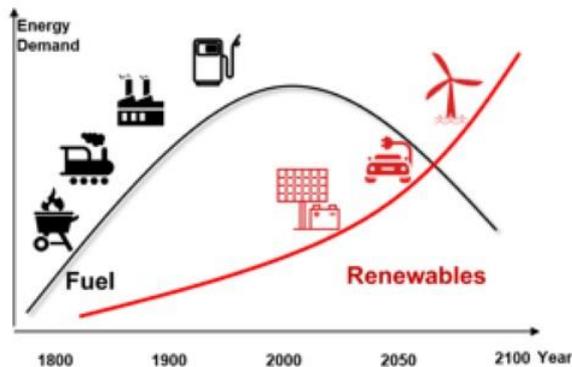
发现4:

碳中和将加剧各国对
关键金属的争夺

全球能源与资源格局将发生**根本性变革**

中科院城市环境研究所「物质循环与城市代谢」团队制作

传统能源



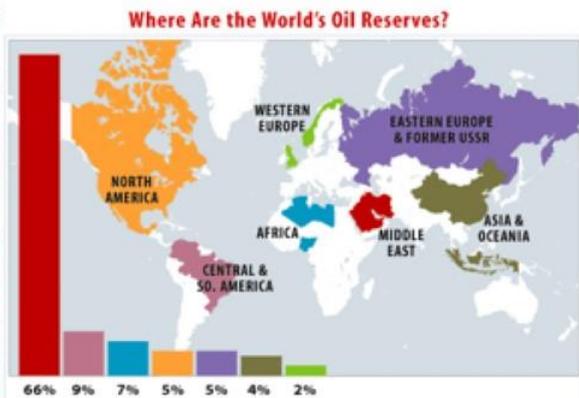
From (Wang P et al, 2019)



The Material Basis of Energy Transitions
 Edited by
 Alena Betscher
 Alexandra Pottmann

课题组参与第三章的编写

关键矿产



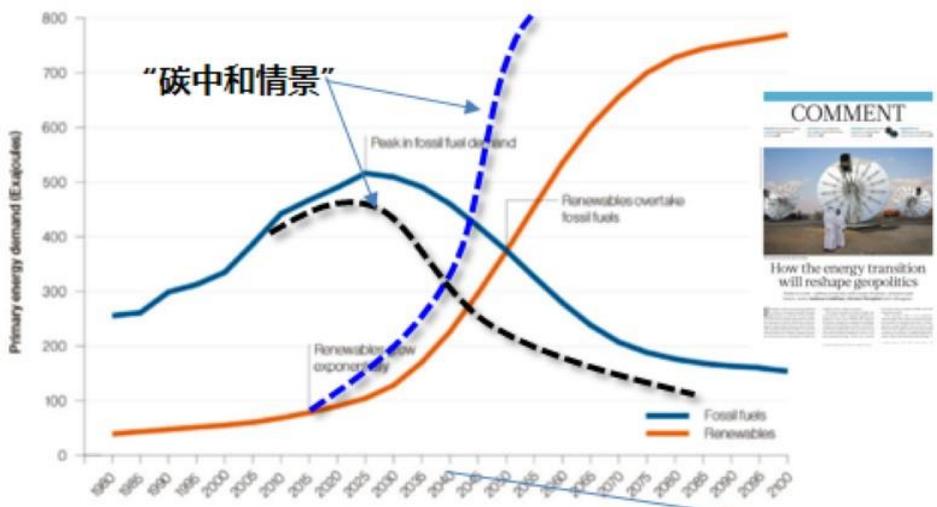
From (PMF IAS, 2019)



From (BP 2012)

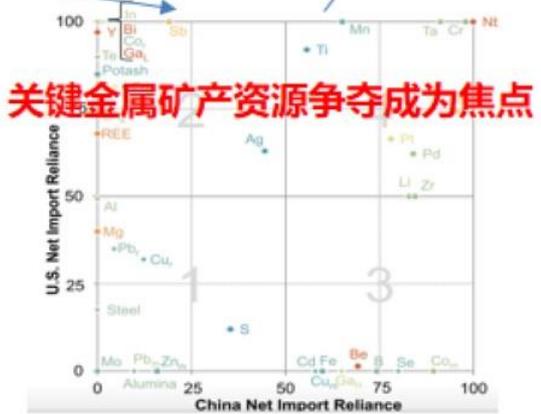
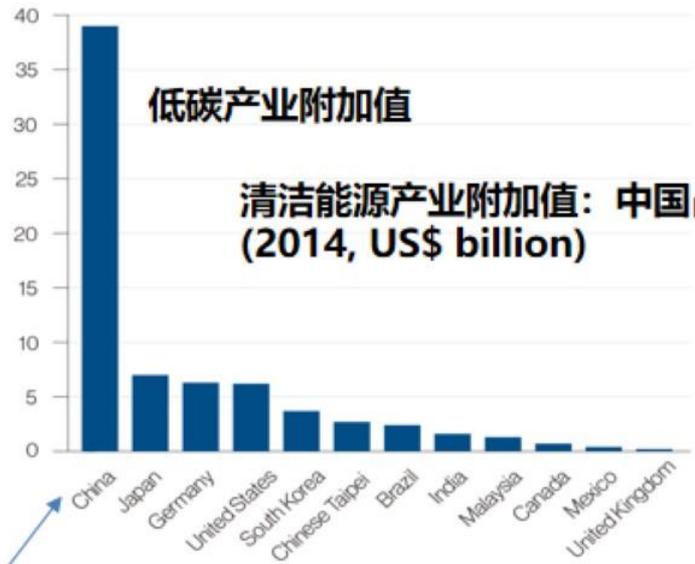
碳中和将加快重塑全球能源与资源地缘格局

(1) “碳中和” 将加速化石能源地缘力量衰退



Source: Shell Sky Scenario, 2018.

(2) 低碳制造与技术强国在国际上地缘力量增强

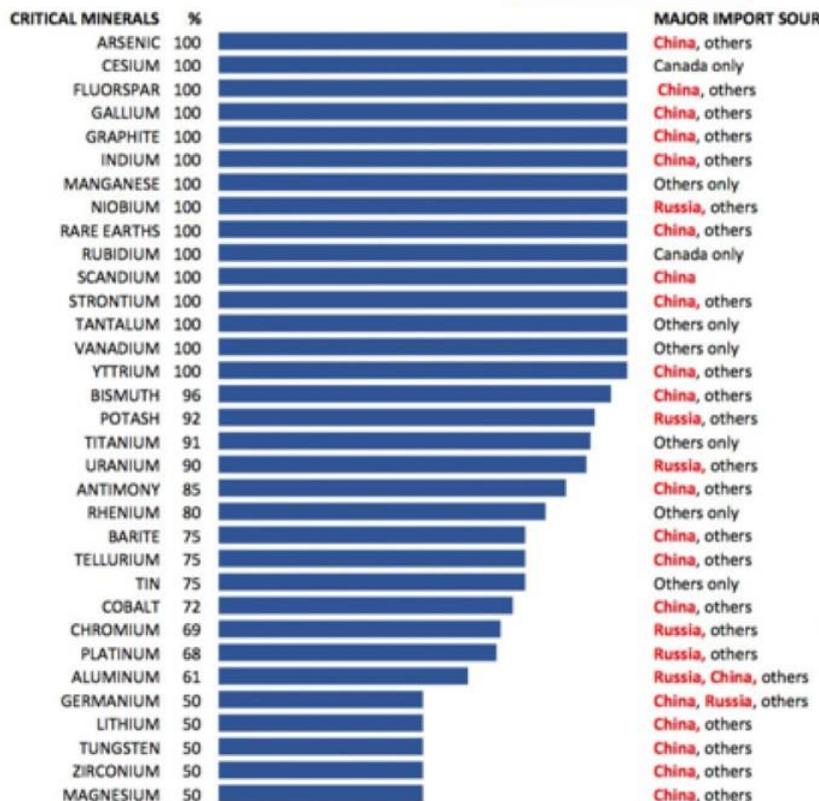


Gulley A L, Nassar N T, Xun S. China, the United States, and competition for resources that enable emerging technologies[J]. Proceedings of the National Academy of Sciences of the United States of America, 2018:4111-4115.

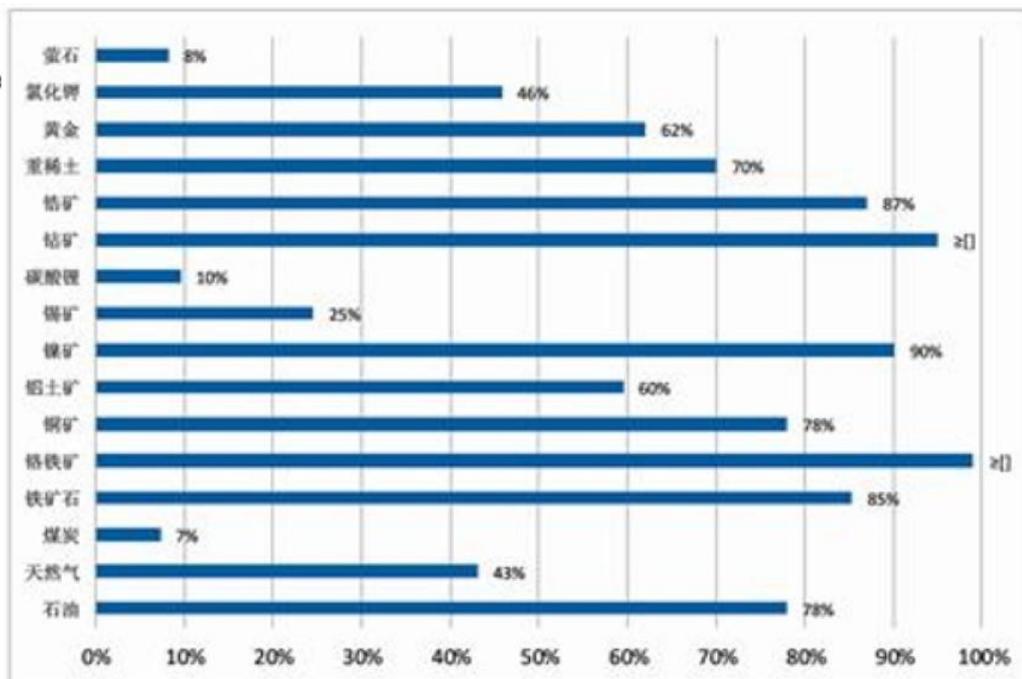
我国面临的挑战十分严峻

将中国视为敌手

U.S. Critical Mineral Import Dependence:
All Over 50%, Many at 100%, Too Many From Adversaries



我国关键金属资源对外依存度将持续上升



我国关键金属产业高质量发展能力不足，无法有效支撑我国“碳中和”目标的需求

After U.S. Geological Survey (USGS) 2017 Mineral Commodity Summaries, U.S. Net Import Reliance; and Department of the Interior, February 15, 2017 Federal Register "Draft List of Critical Minerals"

低碳能源的金属约束小结

- 低碳能源技术依赖于多种金属材料
- 短期产能不足和长期资源短缺并存
- 不可再生资源约束：能源→材料
- 金属生产能耗可抵消低碳技术的减排效果
- 中国通过提供金属为碳减排作出巨大贡献
- 地缘政治因素：化石能源→能源+材料

汇报提纲

- 人类世(时代)的物质循环
- 金属-能源关联 与 碳中和
- 研究团队与工作基础简介

研究平台

<http://macycle.org>

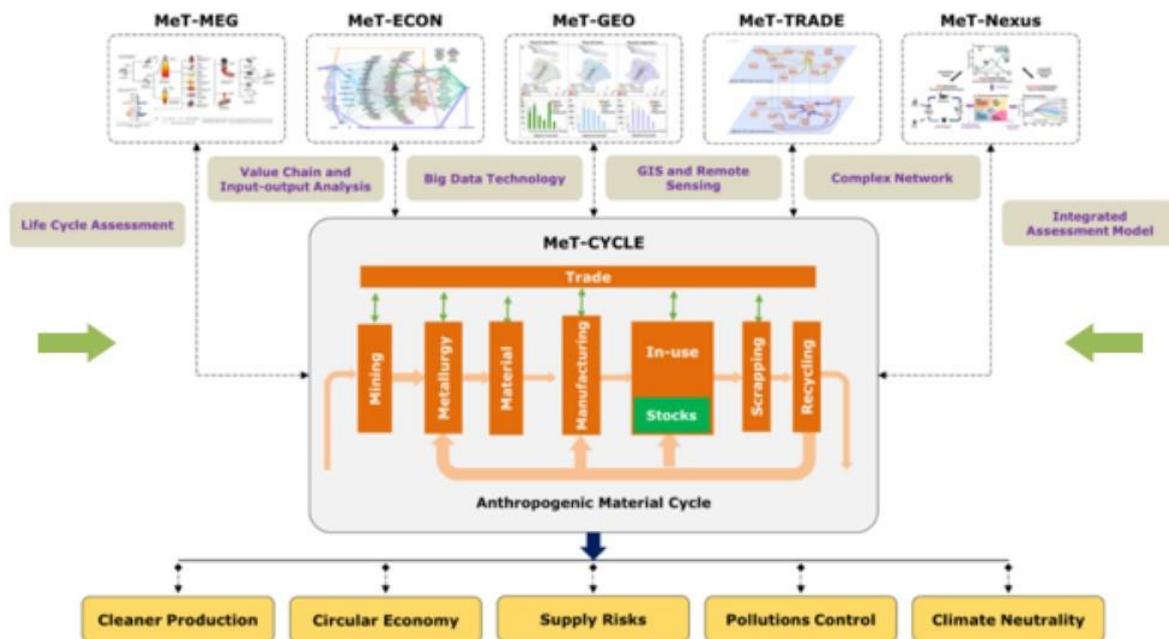
MAC 平台 (Material Cycle and Manufacturing Capital)

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- 贸易、能源
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元数据结构

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- 多区域
- 分元素
- 全链条



方法支撑

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学术论文

围绕物质循环、生态环境效应、绿色低碳发展等研究领域

在 *PNAS*、*Nature Communications*、*One Earth*、*ES&T*、*科学通报*、*资源科学* 等学术期刊发表论文 70 余篇



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