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BIOS

- 莱顿大学工业生态学博士
- 学习和工作经历：耶鲁大学工业生态中心、伦敦帝国理工学院环境政策中心、莱顿大学环境科学研究所
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- **Study and work experience: the Centre for Industrial Ecology of Yale University, the Centre of Environmental Policy of Imperial College London, the Institute of Environmental Sciences of Leiden University**
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研究方向： 工业生态学、物质流分析与生命周期评价及其在资源、废弃物与环境管理中的应用、综合评价模型、能源与交通技术评价、物质-能源-水-气候关系

Research Interests: industrial ecology, material flow analysis and life cycle assessment and their applications in resources, waste, and environmental management, integrated assessment modeling, energy and transportation technologies assessment, and material-energy-water-climate nexus

ADB

Final Dissemination Workshop
ADB TA Study on Municipal Solid Waste Regional Integrated Management Model for Beijing-Tianjin-Hebei

25-26 AUGUST 2022

Circular Economy - An Industrial Ecology Perspective
循环经济 – 工业生态学视角

Ayman Elshkaki

Material Flow Analysis (MFA)
物质流分析 （MFA）

- Material flow analysis (MFA), one of the industrial ecology tools, is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material

  物质流分析（MFA）是工业生态学的工具之一，它是对空间和时间定义的系统内的物质流量和存量的系统评估。物质流分析连接物质的来源、途径、中间点和最终汇

- Substance (Cd, Cu, Pb, Co)
  物质（镉、铜、铅、钴）
- Material (Plastic, Biomass)
  材料（塑料、生物质）
- Product (Cars, Batteries)
  产品（汽车、电池）
- Firm (Single Plant, Company)
  企业（单一工厂、公司）
- Sector (Energy, Transportation)
  部门（能源、运输）
- Region (Total Material Requirement)
  区域（总材料需求）

- Develop environmental policy for substances
  制定与物质相关的环境政策
- Evaluation of product environmental impacts
  产品环境影响评价
- Designing strategies for recycling and disposal.
  设计回收和处理策略
- Identification of accumulation and depletion of materials
  确认材料的积累和损耗
- Providing firm environmental performance data
  提供企业环境绩效数据
- Derivation of sustainability indicators
  推导可持续性指标
- Development of material flow account for use in official statistics
  开发用于官方统计的物质流核算

Haes et al. 1997; Brunner & Rechberger 2004

Nickel and Neodymium Cycles – Two extreme end of life recycling
镍与钕循环 —— 循环的两个极端

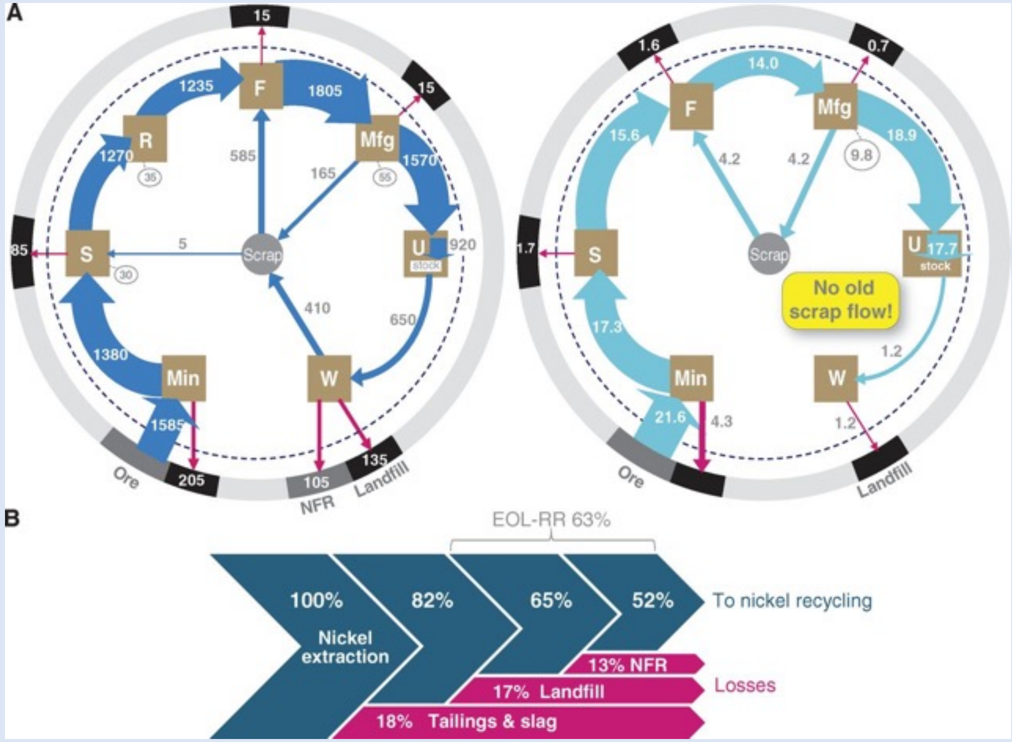
- Out of the 650 Gg Ni discarded from use，about 410 Gg is returned (2/3 of the discarded)
- 在650 Gg 的废弃镍中，约410 Gg被回收（占废弃镍的2/3）
- Ni discarded and manufacturing scrap provides about 1/3 of the Ni required for fabrication and manufacturing
- 废弃镍和制造废弃物提供了约1/3的制造和生产所需的镍
- Out of the 15.6 Gg Nd used in fabrication and manufacturing, only 1.2 Gg was discarded (the majority is stock in use) and little to none is currently being recycled
- 在制造和生产过程使用的15.6Gg钕中，只有1.2Gg被丢弃（大部分是使用中的存量），目前几乎没有被回收

Material efficiencies across nickel's life cycle.
镍生命周期内的材料效率

- 82% enters fabrication, manufacturing, and end use; and 65% enters the recycling processes;
- 82%进入制造、生产和终端使用；65%进入回收流程
- 52% is recycled for another use in which nickel's properties are required (functional recycling)
- 52%被回收用于需要镍特性的其他用途（功能性回收）
- Losses across one life cycle is 48%
- 一个生命周期内的损耗是48%

Reck and Graedel, Science 337, 6095

Global Ni Cycles（全球镍循环）2005　　Global Nd Cycles（全球钕循环）2007



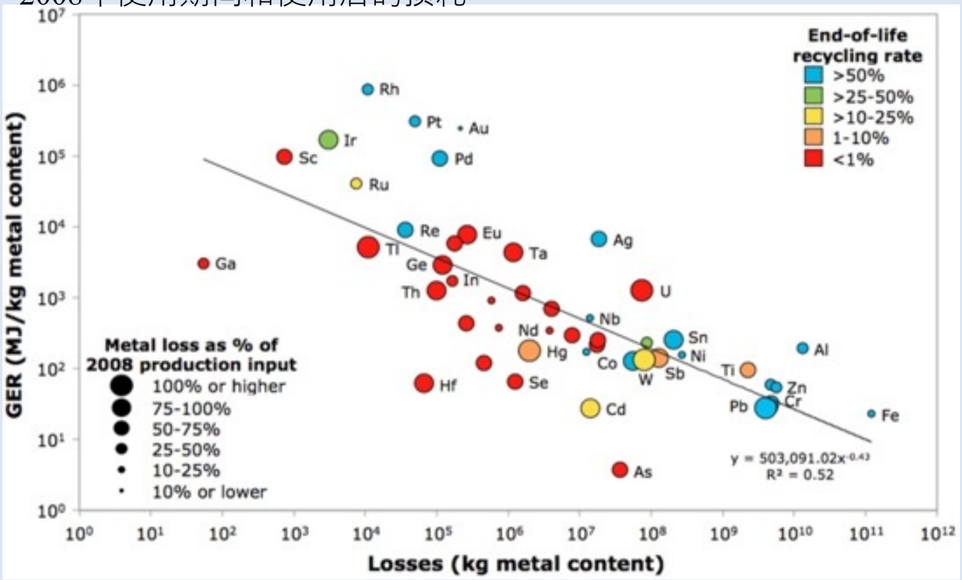
Flows in thousands of metric tons （流量以千公吨为单位）
Min, mining（采矿）; S, smelting（冶炼）; R, refining（精炼）;
F, fabrication of semi-products (rolls, sheets, etc.)（半成品制造（卷材、板材等））;
Mfg, manufacturing（生产）;
W, waste management and recycling（废物管理和回收）.
EOL-RR, end-of-life recycling rate（报废回收率）;
NFR, nonfunctional recycling（非功能性回收）.

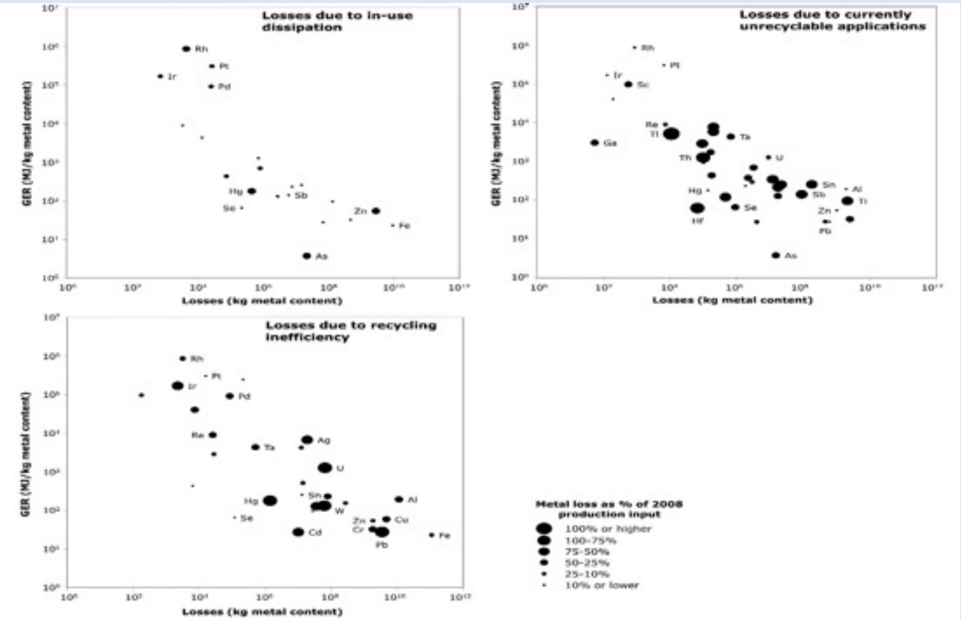
Metal Dissipation and Inefficient Recycling
金属耗散与低效回收

- Several metals have low recycling rate including REEs, Ge, Ga, In, Se, Te which are required for energy transition
  一些金属的回收率较低，包括能源转型所需的稀土、锗、镓、铟、硒、碲等
- The main losses are in the cycles of Eu, Ta, U, Hg, W, Th, Ge, Sc, Hf, Ti, Cd, Ir, Re, Pd
  主要损耗在铕、钽、铀、汞、钨、钍、锗、钪、铪、钛、镉,、铱、铼、钯的循环中

- Dissipation losses in the use phase for most metals is too small
  大多数金属在使用阶段的耗散很小
- The main losses is either due to unrecyclable applications or inefficient recycling
  损耗主要来自不可回收应用或低效率回收
- Losses due to unrecyclable applications is mainly for Ti, Th, Hf, Ga, Sc
  由不可回收应用造成的损耗主要是钛、钍、铪、镓、锗
- Losses due to inefficient recycling is mainly for Ag, Cd, W, Ir, Hg, Pb, Cu
  由低效率回收造成的损耗主要是银、镉、 钨、铱、汞、钯、铜

losses during and after use in year 2008
2008年使用期间和使用后的损耗

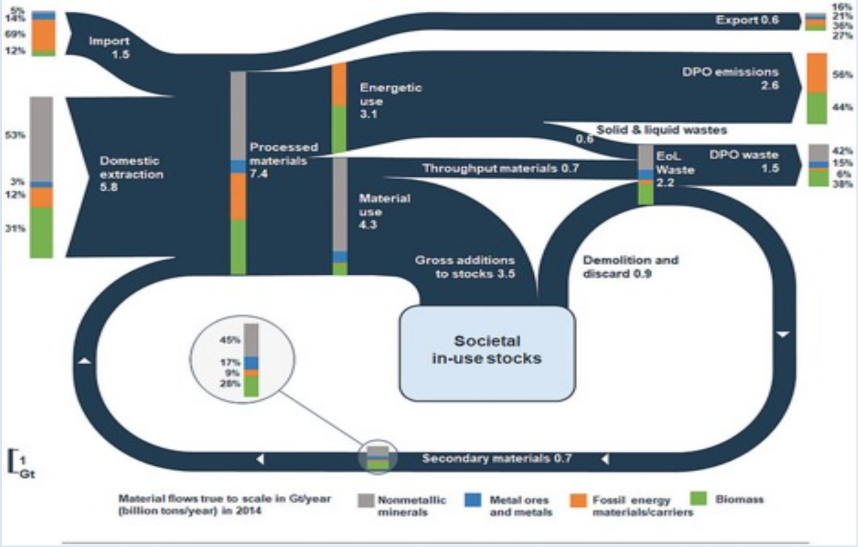




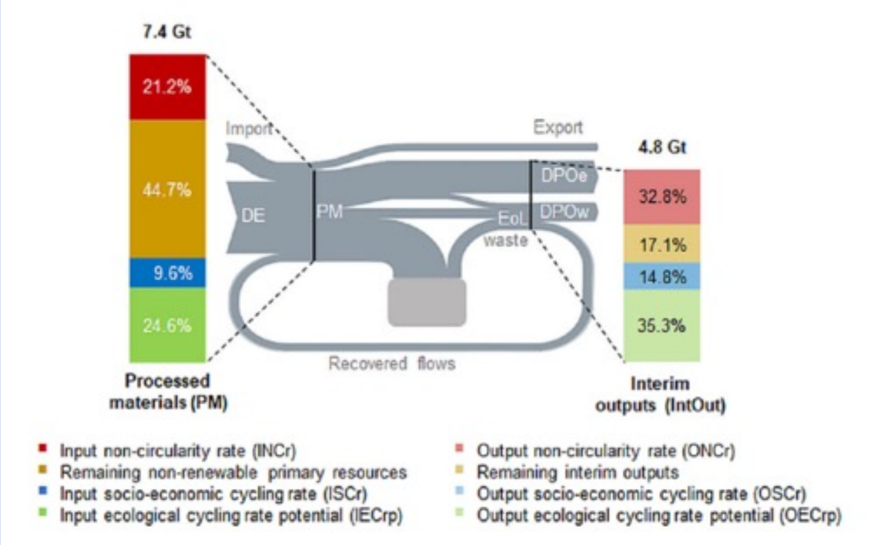
Ciacci et al., 2016. Environ. Sc. & Tech. 50, 11394

Economy Wide Material Flow Analysis (MFA) – EU
经济系统物质流分析（MFA）—— 欧盟

Material flows through the EU28 economy
欧盟28国经济体物质流



Input and output side CE indicators
输入和输出侧循环经济指标



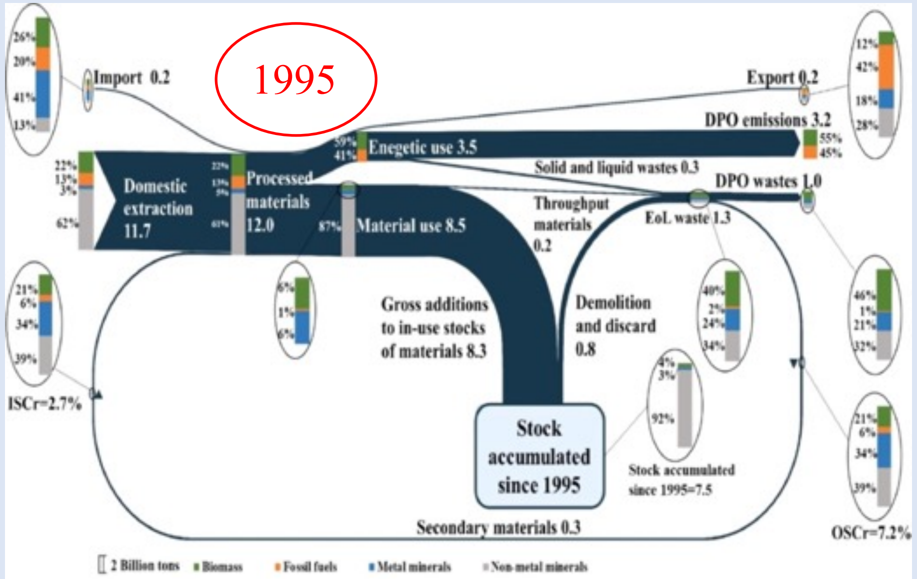
➢ Circularity rates (%) （循环率）

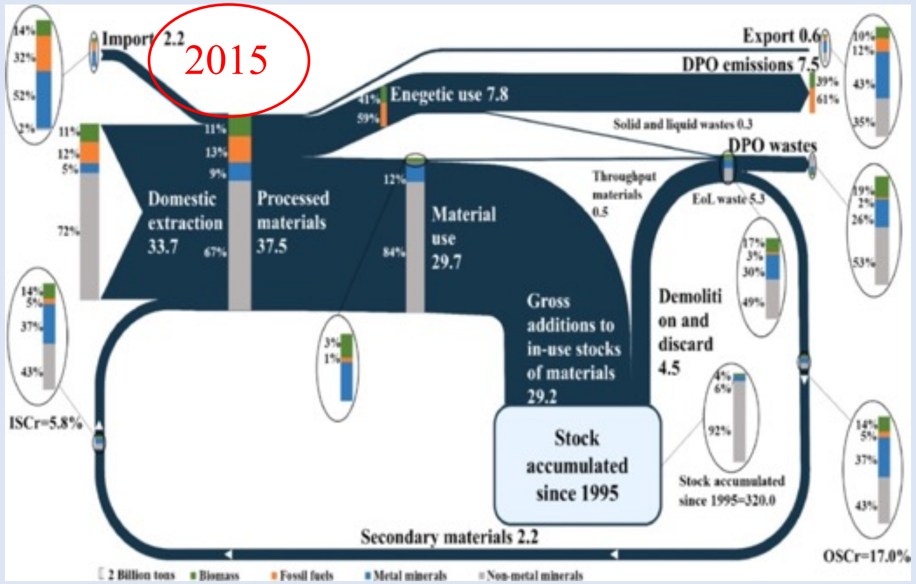
- Input socioeconomic cycling rate ISCr = Share of secondary materials in PM
  输入社会经济循环率=再生材料在加工材料中的份额
- Output socioeconomic cycling rate OSCr = Share of secondary materials in IntOut
  产出社会经济循环率=再生材料在临时产出中的份额
- Input ecological cycling rate potential (IECrp) = Share of DMC of primary biomass in PM
  输入生态循环率潜力=加工材料中国内材料消耗初级生物质的份额
- Output ecological cycling rate potential (OECrp) = Share of DPO biomass in IntOut
  输出生态循环率潜力=临时产出中国内加工产出生物质的份额
- Input non-circularity rate INCr = Share of eUse of fossil energy carriers in PM
  输入非循环率=加工材料中化石能源在能源使用中的份额
- Output non-circularity rate ONCr = Share of eUse of fossil energy carriers in IntOut
  产出非循环率=临时产出中化石能源在能源使用中的份额

Mayer et al., 2018. J.Ind. Ecol. 23, 62-76

Economy Wide Material Flow Analysis (MFA) – China
经济系统物质流分析（MFA）—— 中国

- Materials processed (PM) increased by a factor of 3.1
  加工材料增长了3.1倍
- Domestic extraction of PM decreased from 97.2% to 90%
  国内加工材料提取率从97.2%降至90%
- Material use (required for building up residential, commercial and industrial infrastructure and transport and communication networks) of all processed materials grew from 70.5% to 79.1% in 2015
  所有加工材料的材料使用量（建筑住宅、商业和工业基础设施以及运输和通信网络）在2015年从70.5%增长至79.1%
- Gross addition to stock (GAS) increased by a factor of 3.5
  存量增加总额增长了3.5倍
- Accumulated stock, which provides the physical basis of China's improving infrastructure, reached 320 billion tons.
  为中国改善基础设施提供物质基础的累计存量达到3200亿吨
- China's DPO of emissions annual increasing rate of 4.3%
  中国国内加工产出排放量年增长率为4.3%
- While material use, waste flows and emissions accelerated, China's circularity rates also increased significantly.
  在材料使用、废物流动和排放加速的同时，中国的循环率也显著提高
- Input socioeconomic cycling rate (ISCr, SM share of PM) increased from 2.7% to 5.8%
  输入社会经济循环率从2.7%增至5.8%
- Output socioeconomic cycling rate (OSCr, SM share of IntOut) increased from 7.2% to 17.0%
  产出社会经济循环率从7.2%增至17.0%

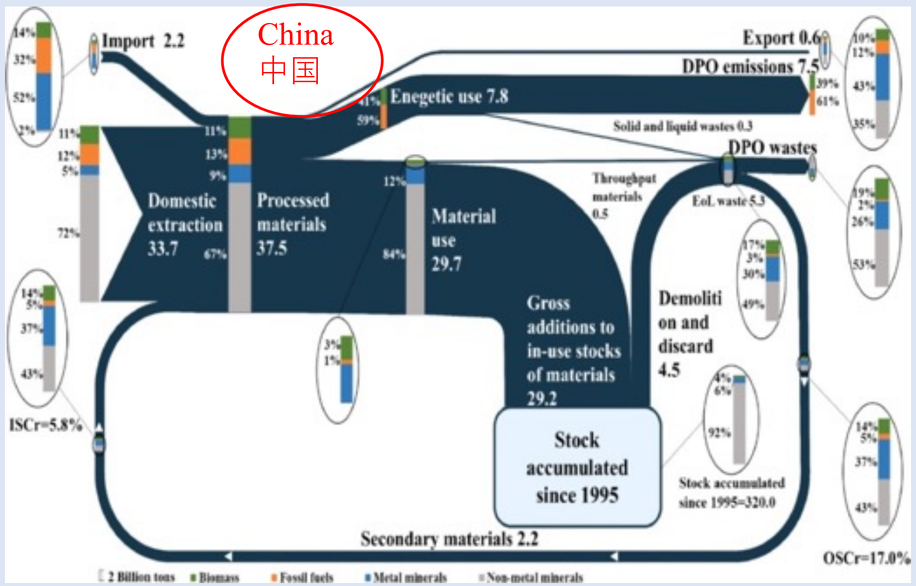


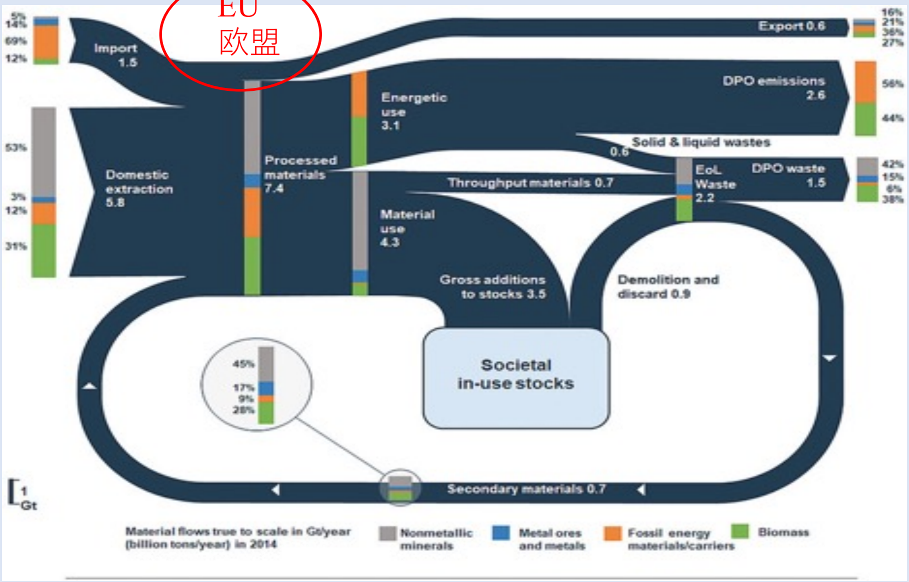


Wang et al., 2020 RCR, 163, 105070

Economy Wide Material Flow Analysis (MFA) – China and EU
经济系统物质流分析（MFA）—— 中国和欧盟

- Input socioeconomic cycling rate (ISCr) in the EU was 9.6% in 2014, while China's ISCr is 5.8%
  2014年，欧盟的输入社会经济循环率为9.6%，中国的为5.8%
  - ISCr in China is significantly lower mainly due to
    中国的输入社会经济循环率显著低于欧盟的主要原因
    - the lack of a sound recycling system
      缺乏健全的回收系统
    - the large amount of gross addition to stock (GAS).
      存量增加总额巨大
- Output socioeconomic cycling rate (OSCr) in the EU was 14.8%, while China's OSCr is 17%
  产出社会经济循环率在欧盟是14.8%，在中国是17%
  - OSCr in China is higher due to
    中国的产出社会经济循环率较高的原因有
    - most of China's SM is from industrial solid waste
      中国的再生材料大部分来自工业固体废物
    - the central government has imposed mandatory targets (utilization efficiency of general industrial solid waste) for local governments and enterprises in recent years
      近年来中央政府为地方政府和企业设定了前置性目标（一般工业固体废物的利用效率）





Wang et al., 2020 RCR, 163, 105070; Mayer et al., 2018. J ind. Ecol. 23, 62-76

Relationship between CE indicators and existing policy indicators
循环经济指标与现存政策指标之间的关系

Indicator 指标	Purpose 目标	Policy 政策	13th Five Year Plan 第13个五年计划 (2015–2020)	Green Development Indicator System 绿色发展指标体系	Assessment Target System of Ecological Civilization 生态文明建设评估目标体系
DMC	Consumption pressure 消费压力	Consumption policy 消费政策	Share of Non-Fossil Fuels in Primary Energy Consumption 非化石燃料在一次能源消费中的份额	Total Energy Consumption; Share of Non-Fossil Fuels in Primary Energy Consumption. 能源消费总量；非化石燃料在一次能源消费中的份额	Total Energy Consumption; Share of Non-Fossil Fuels in Primary Energy Consumption 能源消费总量；非化石燃料在一次能源消费中的份额
RE=GDP/DMC	Efficiency of resource use 资源使用效率	Resource efficiency policy 资源效率政策	Reduction in Energy Consumption per unit of GDP 每单位GDP减少能源消耗	Resource Productivity; Reduction in Energy Consumption per unit of GDP 资源生产率；每单位GDP能耗降低	Reduction in Energy Consumption per unit of GDP 每单位GDP能耗降低
DPO	Pressure on domestic ecosystem 本地生态系统压力	Waste or emission management policy 废物或排放管理政策	Reduction in Total Emission of COD, Ammonia Nitrogen, Sulfur Dioxide, and NOx; Reduction in CO2 Emission per unit of GDP. 减少COD、氨氮、二氧化硫和氮氧化物的总排放量；每单位GDP减少二氧化碳排放量	NOx; Harmless Treatment Ratio of Household Waste; Centralized Sewage Treatment Ratio; Reduction in CO2 Emission per unit of GDP 氮氧化物；生活垃圾无害化处理率；污水集中处理率；单位GDP减少二氧化碳排放量	NOx; Reduction in CO2 Emission per unit of GDP. 氮氧化物；每单位GDP减少二氧化碳排放量
ISCr	Cycling condition on input side 循环输入侧	CE policy 循环经济政策			
OSCr	Cycling condition on output side 循环产出侧	CE policy 循环经济政策		Utilization Efficiency of Crop Straw; Utilization Efficiency of General Industrial Solid Waste. 农作物秸秆利用效率；一般工业固体废弃物利用效率	

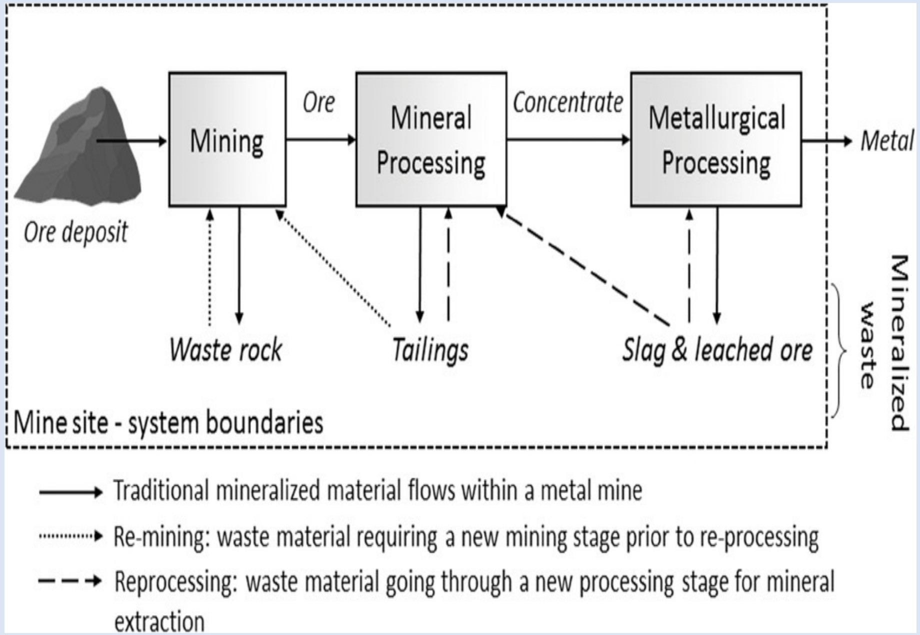
Wang et al., 2020 RCR, 163, 105070

Circular Economy at Mine Site Level
矿区层面的循环经济

CE concept applied to mining operation at the Mount Morgan mine in Australia that has been occupied by three mining projects, two of them are mine waste reprocessing projects
循环经济概念应用于澳大利亚摩根山矿区的采矿作业，该矿区由三个采矿项目组成，其中两个是矿山废物再处理项目

Indicators （指标）

- Total production (TP) （总产量）
- Total Production From Waste (TPW) （源自废物的总产量）
- Mineral Losses to New Waste (MLNW) （新废物造成的矿物损失）
- Total Mineral Losses to Waste (TMLW) （废物造成的矿物损失总额）
- Total Material Moved (TMM) === total material requirement
  搬运原料总量=原料需求总量
- Total Material Processed (TMP) === direct material requirement
  加工原料总量=原料直接需求总量
- Total Reactive Waste Generation (TRWG)（活性废物生产总量）
- Net Waste Generation (NWG)（净废物产生量）



Material Efficiency (ME)（原料效率）

the ratio between total production and total material moved (TP/ TMM)
总产量与搬运原料总量之比

Extraction inefficiency (EI) （提取无效率）

a percentage that represents the total losses that occurred during the mining project divided by the mineral content of the input material (MLNW / (MLNW + TP))
新废物造成的矿物损失除以矿物损失与总产量之和

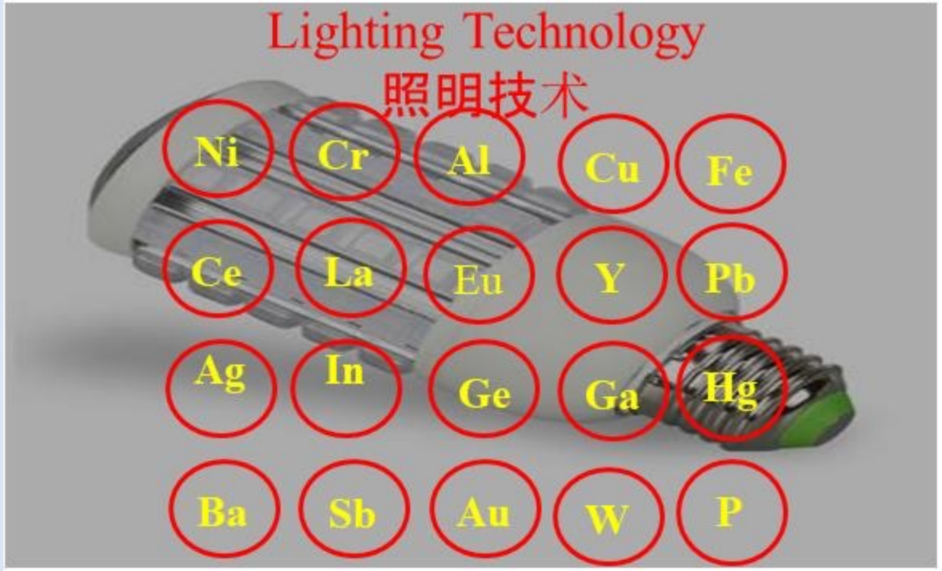
New area impacted (NAI) （受影响新区）

represents the geographical area impacted by mining activities (open pits and waste deposits, such as waste rock piles, tailings dams, but also areas covered by infrastructure)
表示受采矿活动影响的地理区域（露天矿和废矿床，如废石堆、尾矿坝，以及基础设施覆盖的区域）

L`ebre et al., 2017, J ind. Eco. 21, 662-672

Energy-Material Nexus
能源-原料关联

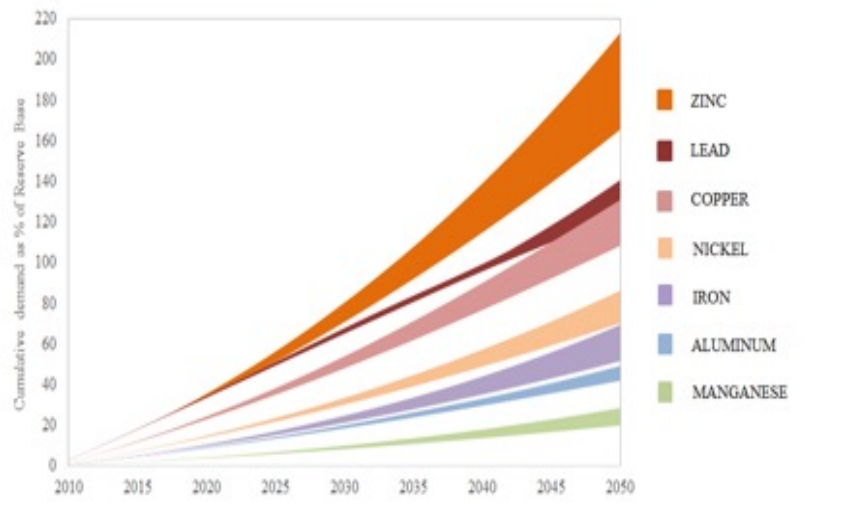
Materials required for supply, demand, and storage energy technologies
供应、需求和储存能源技术所需的原料



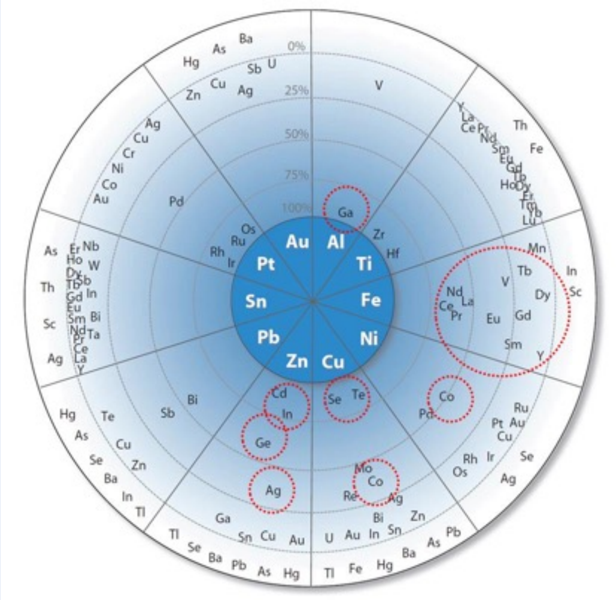
Energy-Material Nexus
能源-原料关联

Materials required for supply, demand, and storage energy technologies
供应、需求和储存能源技术所需的原料

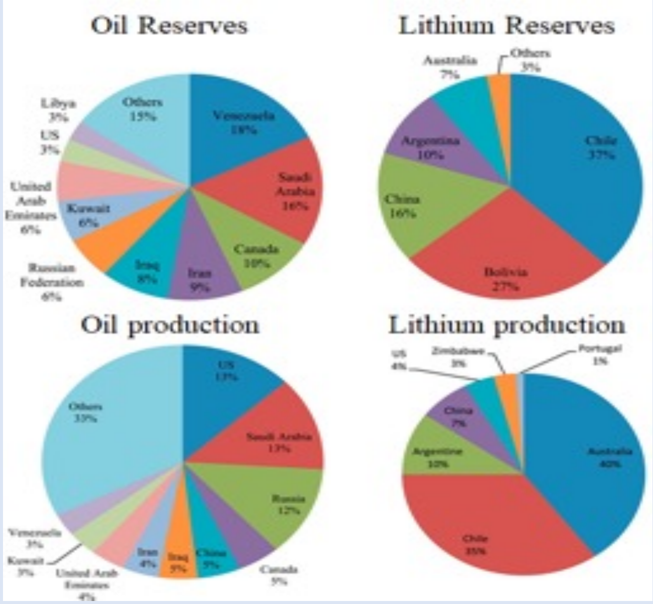
- Resources availability（资源供应）
- Production capacity（产能）
- Co-production（联合生产）
- Geographical Concentration（地域集中度）
- Environmental impacts （环境影响）



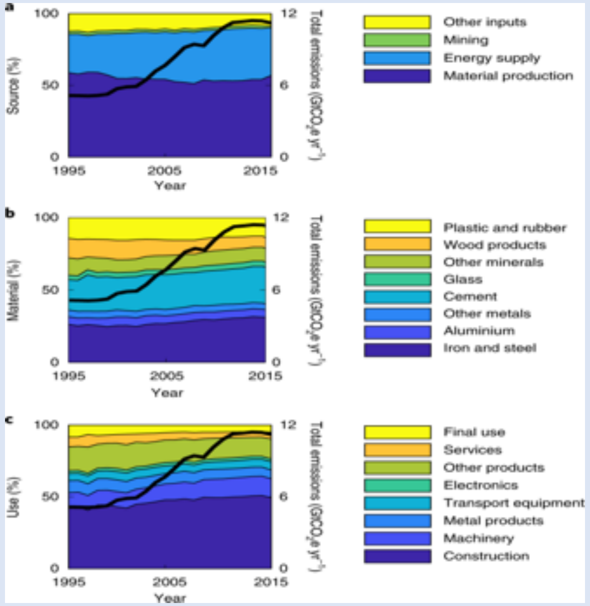
Elshkaki et al., 2018. Environ. Sc. and Techn., 52, 5, 2491



Nassar et al., 2015, Sci. Adv. e1400180



Hache, 2018, International Economics, 156, 127



Hertwich, 2021. Nature Geoscience, 14, 151

Energy-Material Nexus
能源-原料关联

- ➢Materials required for energy technologies
  能源技术所需的原料

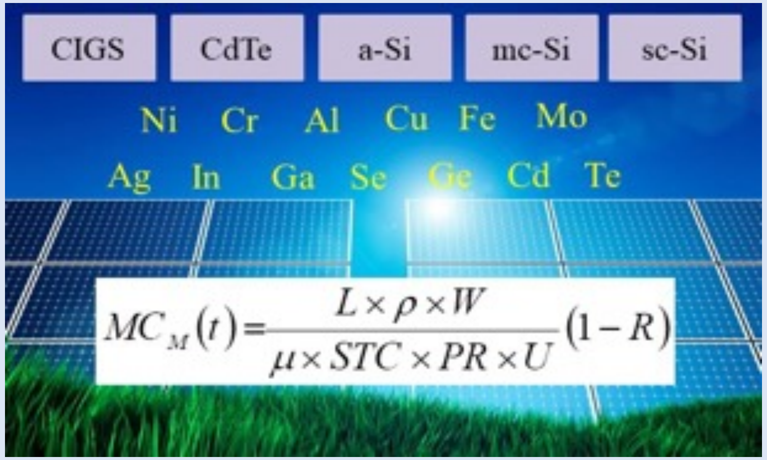
Energy Scenarios – Energy and IAM models
能源情景 – 能源和综合评估模型

- The demand for energy
  能源需求
- Market share of energy technologies
  能源技术的市场份额
- Market share of sub-technologies
  自技术的市场份额

Materials Scenarios
原料情景

- Material content
  原料内容
- Life time of energy technologies
  能源技术寿命
- Substitution (Products, Components, Substances)
  替代物（产品、成分、物质）
- Technological development
  技术发展

- ➢ Energy required for materials and climate implications
  原料和气候不影响的能源需求
- Ore grade, Production processes, Energy efficiency, Energy mix
- 矿石品味, 生产过程, 能源效率, 能源组合

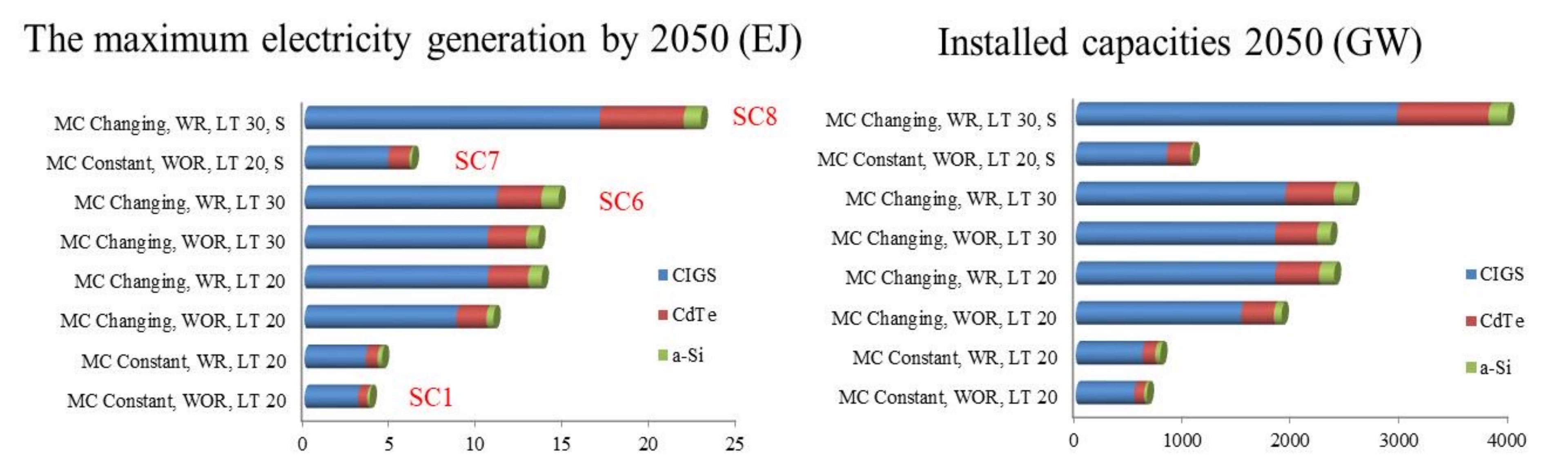


- ➢ Material Content (MC) is assumed constant in one scenario and changing based on changes in
  假设原料内容（MC）在一种情景是恒定的，而另一种情景则基于下方的变化而变化
  - ➢ Absorber layer thickness (*L*), Layer density (*ρ*)
    吸收层厚度,层密度
  - ➢ Metal mass fraction in layer (*W*)
    层内的金属质量分数
  - ➢ Metal utilization rate (*U*), Metal recovery rate (*R*)
    金属利用率,金属回收率
  - ➢ Conversion efficiency (*μ*)
    转换效率
  - ➢ Irradiation (*STC*), Performance ratio (*PR*)
    辐照,性能比
- ➢ Life time (LT) assumed 20 and 30 years
  寿命（LT）假设为20年和30年
- ➢ Recycling. Two scenarios for material recycling rate have been used
  回收。两个原料回收率情景

Elshkaki 2019. Scientific Reports, 9, 19238

Energy-Material Nexus – Global PV Solar Potential
能源-原料关联 ——全球光伏太阳能的潜力

- The decrease in MC would increase electricity generation by thin film PV technologies by 190 %
  原料内容的减少将使薄膜光伏技术的发电量增加190%
- The increase in the LT from 20 to 30 years would increase electricity generation by thin film PV technologies by 25 %
  寿命从20年增加到30年将使薄膜光伏技术的发电量增加25%
- Metals recycling increases electricity generation by thin film PV technologies by 19% if MC is constant and by 26% if MC is changing
  如果原料内容不变，金属回收率将使薄膜光伏技术的发电量增加19%，如果原料内容变化，则增加26%
- The three measures would increase electricity generation by thin film PV technologies by 290%
  这三项措施将使薄膜光伏技术的发电量增加290%

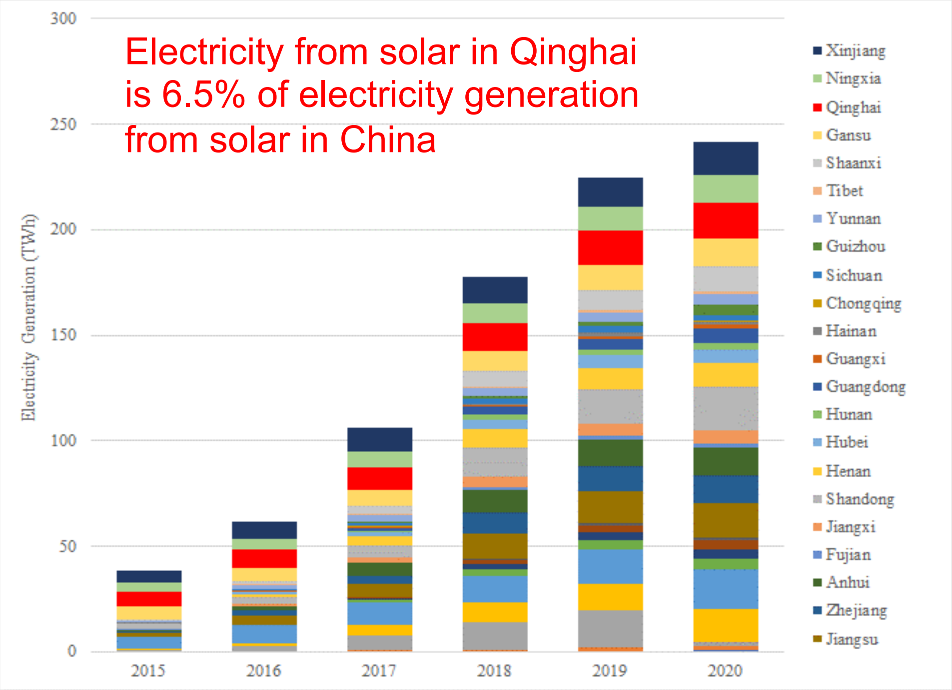


MC Material Content（原料内容）; WR With Recycling（有回收）; WOR Without Recycling（无回收）; LT Life Time（寿命）
S refers to resource availability and production capacity other than those reported by USGS
（除美国地质勘探局报告的资源可用性和生产能力以外的其他资源可用性和生产能力）

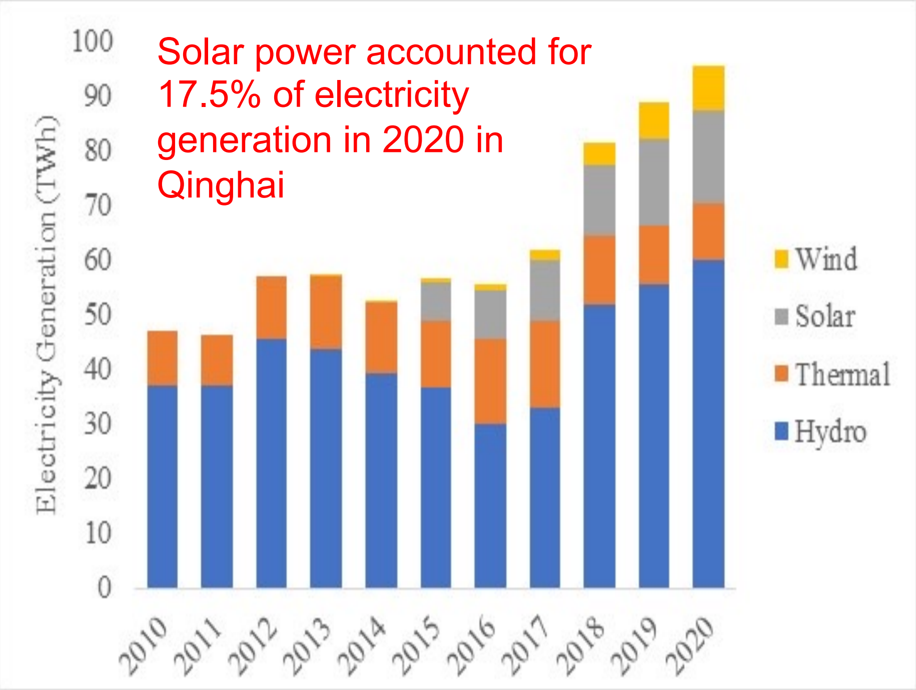
Elshkaki 2019. Scientific Reports, 9, 19238

Analysis of the circular business models for PV industry in Qinghai

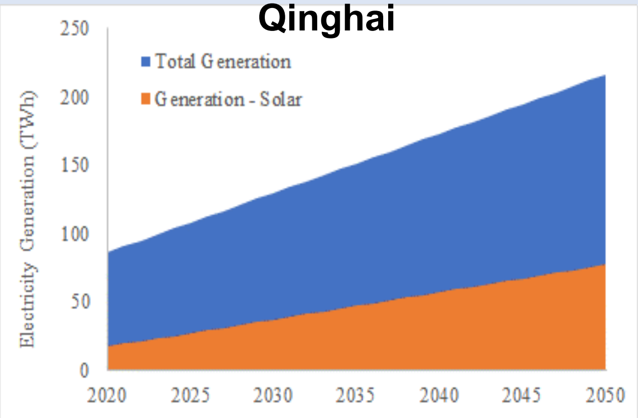
Electricity generation from solar power in different provinces



Electricity generation from different sources in Qinghai



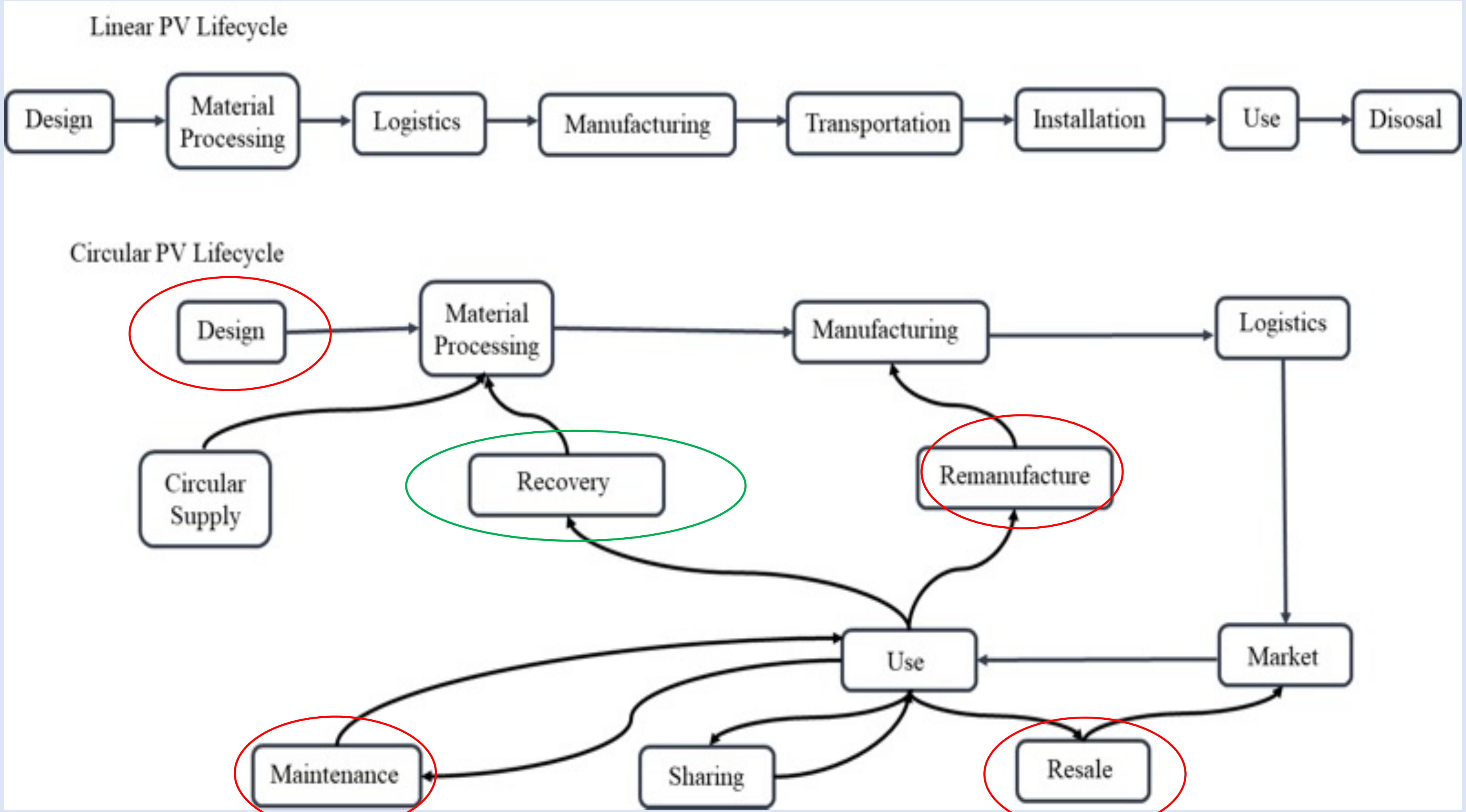
Total electricity generation and the share of solar power between 2020 and 2050 in Qinghai



Solar power is expected to account of 35% of the total electricity generation by 2050

Analysis of the circular business models for PV industry in Qinghai

Linear and circular PV lifecycle

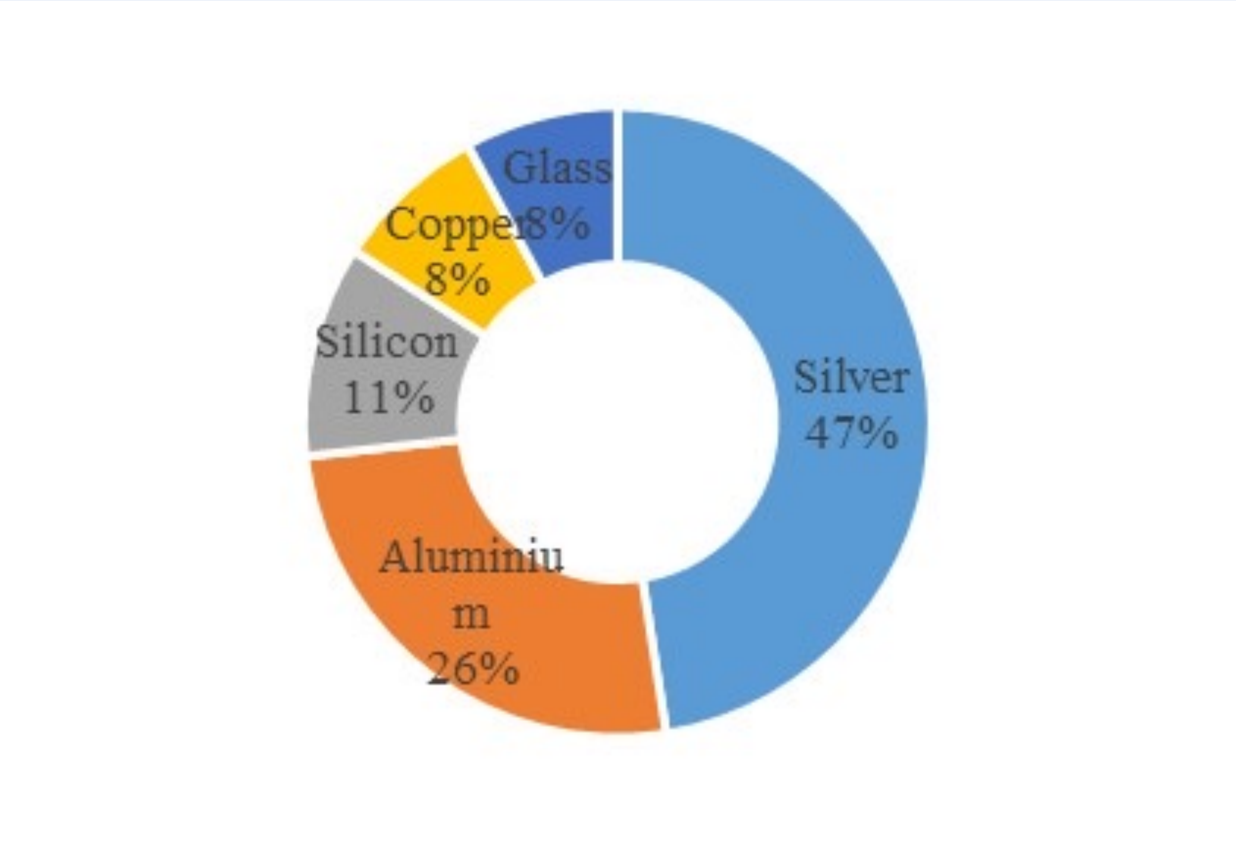


product life extension business model

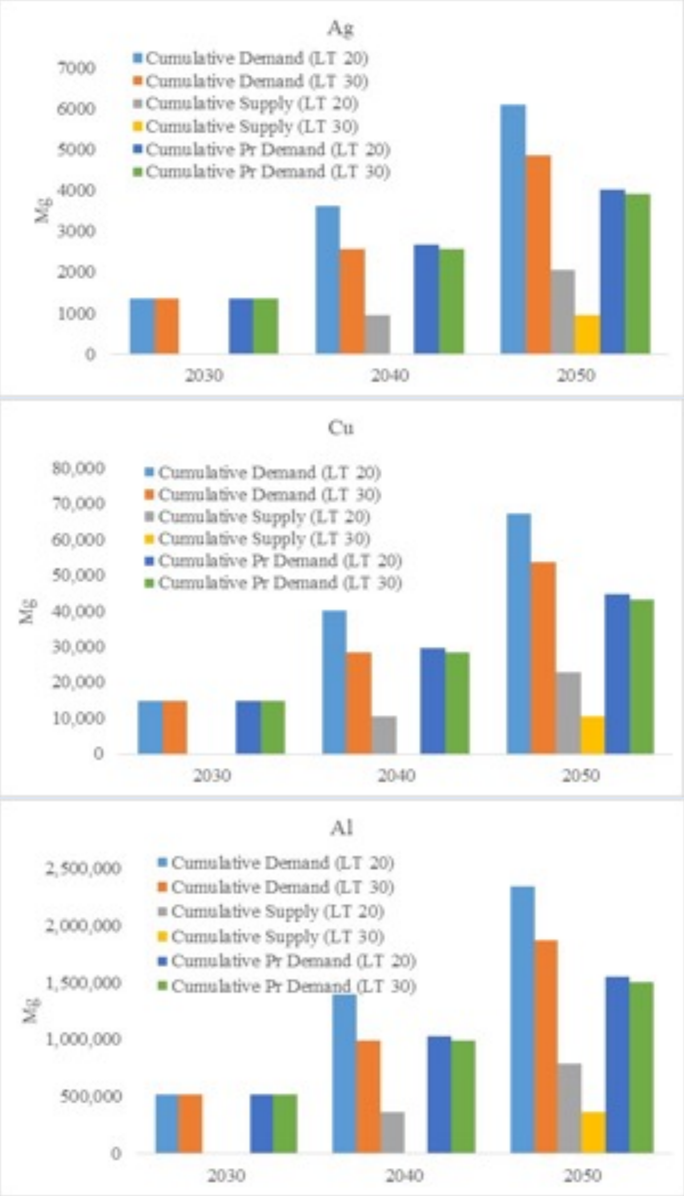
resource recovery business models

Analysis of the circular business models for PV industry in Qinghai

The value of materials in the solar panels



Cumulative demand and supply of materials in the PV solar technology in Qinghai



Energy-Material Nexus - – Electric Vehicles
能源-原料关联 —— 电动汽车

- **Market Trend Scenario (MTSC)**
  市场趋势情景

High Nickel Cobalt Manganese (NCM) and Lithium Manganese Oxide (LMO)
高镍钴锰（NCM）和锂锰氧化物（LMO）

- **Equal Share Scenario (ESSC)**
  等份额情景

- **Low Cost Scenario (LCSC)**
  低成本情景

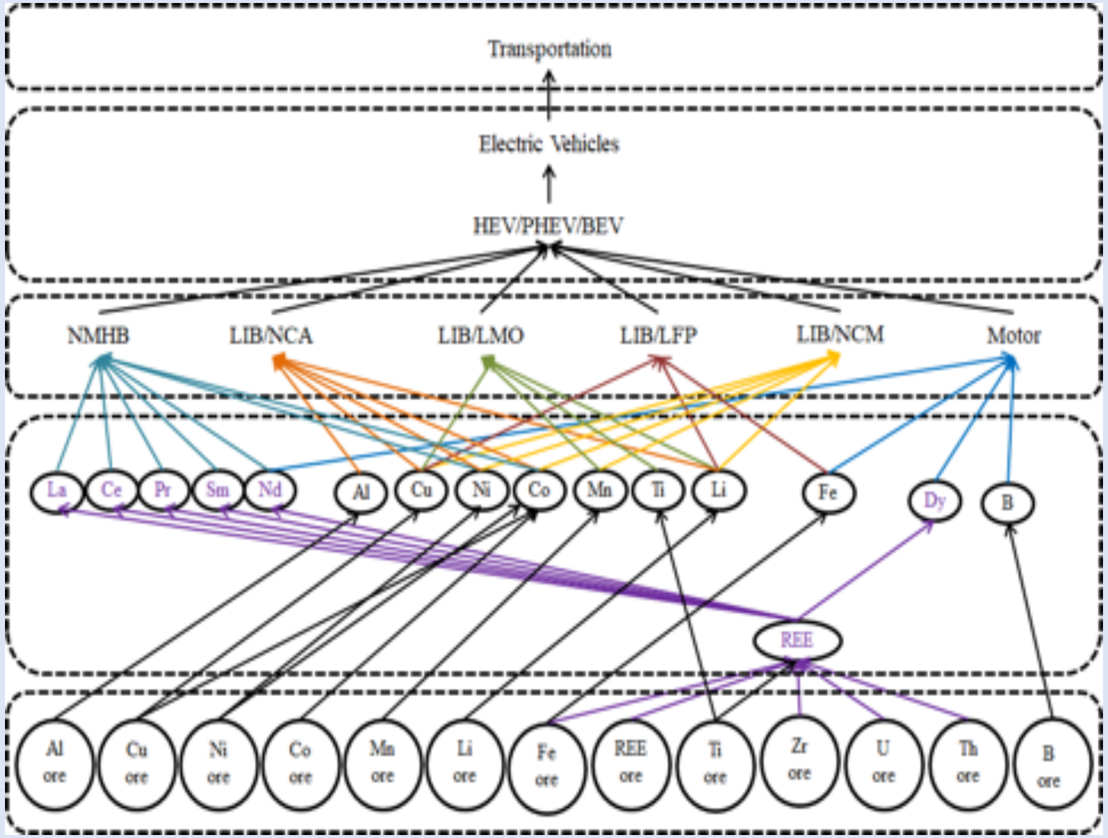
High Lithium Manganese Oxide (LMO) and Lithium Iron Phosphate (LFP)
高锂氧化锰（LMO）和磷酸铁锂（LEP）

- **Other Scenario (OSC)**
  其他情景

NMHB only for HEV
NMHB仅适用于HEV
LMO only for PHEV
LMO仅适用于PHEV
NCA only for BEV
NCA仅适用于BEV

Elshkaki A., 2020. Energy, 202, 117697

Technologies, components, metals and ores connected with electric vehicles
与电动汽车相关的技术、部件、金属和矿石

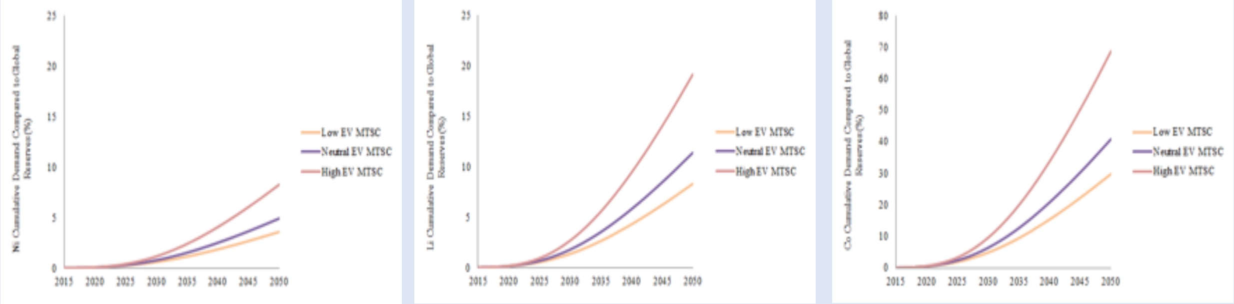


NMHB nickel metal hybrid batteries
镍金属混合电池
LIB lithium ion batteries
锂离子电池
NCA - Nickel Cobalt Aluminum
镍钴铝

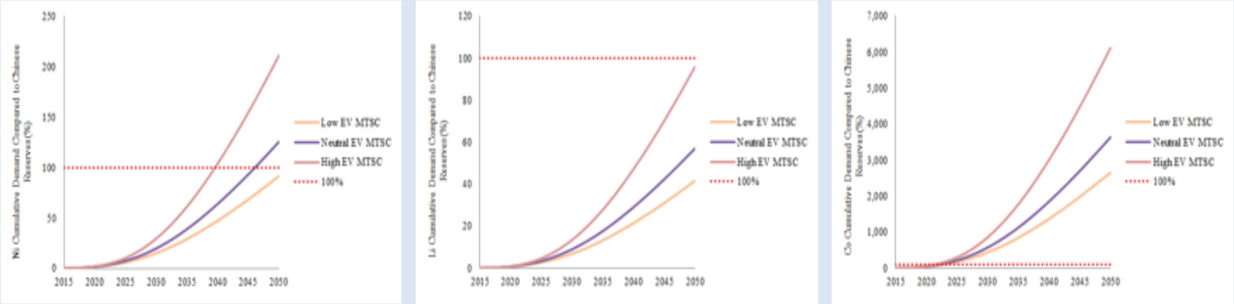
LFP - Lithium Iron Phosphate
磷酸铁锂
LMO - Lithium Manganese Oxide
锂锰氧化物
NCM - Nickel Cobalt Manganese
镍钴锰

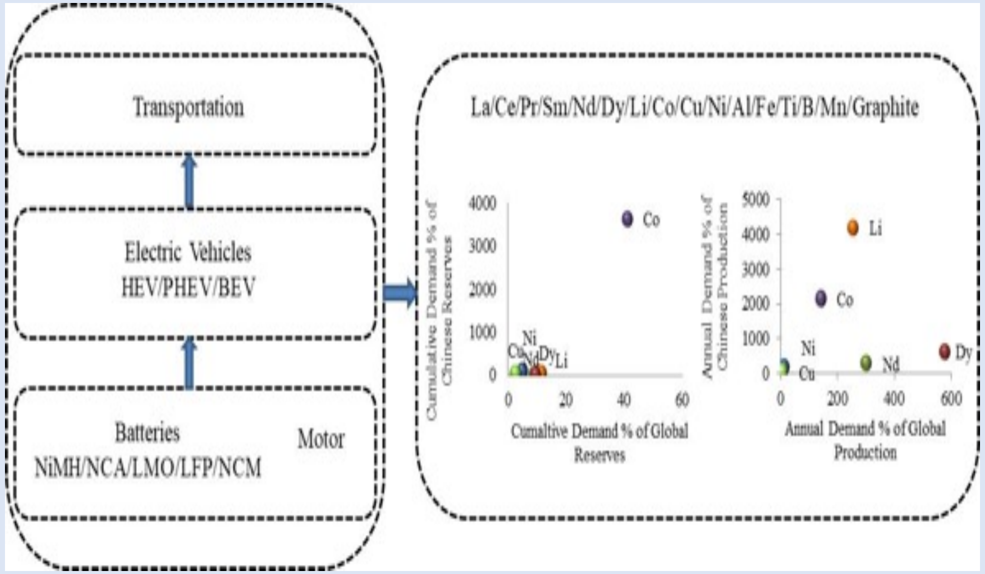
Energy-Material Nexus - – Electric Vehicles
能源-原料关联 —— 电动汽车

Metals cumulative demand in EVs compared to global reserves
电动汽车的金属累积需求与全球储量的比较



Metals cumulative demand in EVs compared to Chinese reserves
电动车的金属累积需求与中国储量比较





- Global availability of resources of all metals needed for EVs are not expected to constraint their long-term development
  电动汽车所需所有金属资源的全球可得性不会在所有情境下限制其长期发展
- Several metals availability in China including Co, Ni, and Cu are expected to constraint EVs development
  预计中国镍、钴和铜的供应将限制电动汽车的发展
- A significant increase in the production capacity of Dy, Li, Nd, and Co on global and Chinese levels and Ni and Cu on a Chinese level is required.
  需要在全球和中国水平上大幅提高镝、锂、钕和钴的产能，并在中国水平上大幅提高镍和铜的产能

Elshkaki A., 2020. Energy, 202, 117697

Energy-Material Nexus - – Electric Vehicles
能源-原料关联 —— 电动汽车

- Extending EVs life time and using more than one battery during their life time would reduce the risks associated with REEs and increase those associated with all other metals.
  延长电动车的使用寿命，并在其生命周期内使用一个以上的电池，将减少与稀土相关的风险，并增加与所有其他金属相关的风险。
- Batteries market share in the *Low Cost Scenario* (highest shares are for LFP and LMO) is better in terms of Ni and Co availability risks, which China has low resources of both
  低成本情景下的电池市场份额（LFP和LMO的份额最高）在镍和钴的可得性风险方面更好，中国的镍和钴资源都很低。
- The market share in the *Market Trend Scenario* (highest share are for NCM and LMO) is better in terms of Li availability risks.
  市场趋势情景中的市场份额（NCM和LMO的份额最高）在锂可得性风险方面更好。
- A combination of the two scenarios could allow several scenarios to be realized.
  两种情景的结合可使一些情景得以实现。
- Increasing resources efficiency (reducing material content) could significantly reduce metals demand and allow several scenarios to be realized.
  提高资源效率（减少物质内容）可以显著减少金属需求，并实现多种情景。
- To improve the development of EVs in China
  促进电动汽车在中国的发展
  - promote the use of all types of EVs, and balance the development and use of different types of batteries,
    推广各类电动汽车的使用，平衡不同类型电池的开发和使用，
  - increase resources efficiency
    提高资源效率
  - secure the availability of Ni, Co, and Cu from outside the country on the short term,
    确保在短期内可从国外获得镍、钴和铜，
  - increase the collection and processing of end of life EVs and their batteries on the long term.
    长期增加报废电动汽车及其电池的收集和处理。

Elshkaki A., 2020. Energy, 202, 117697

Thank You For Your Attention
谢谢！

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