The Role of Technology to A Circular Economy - Facing the Carbon Neutrality

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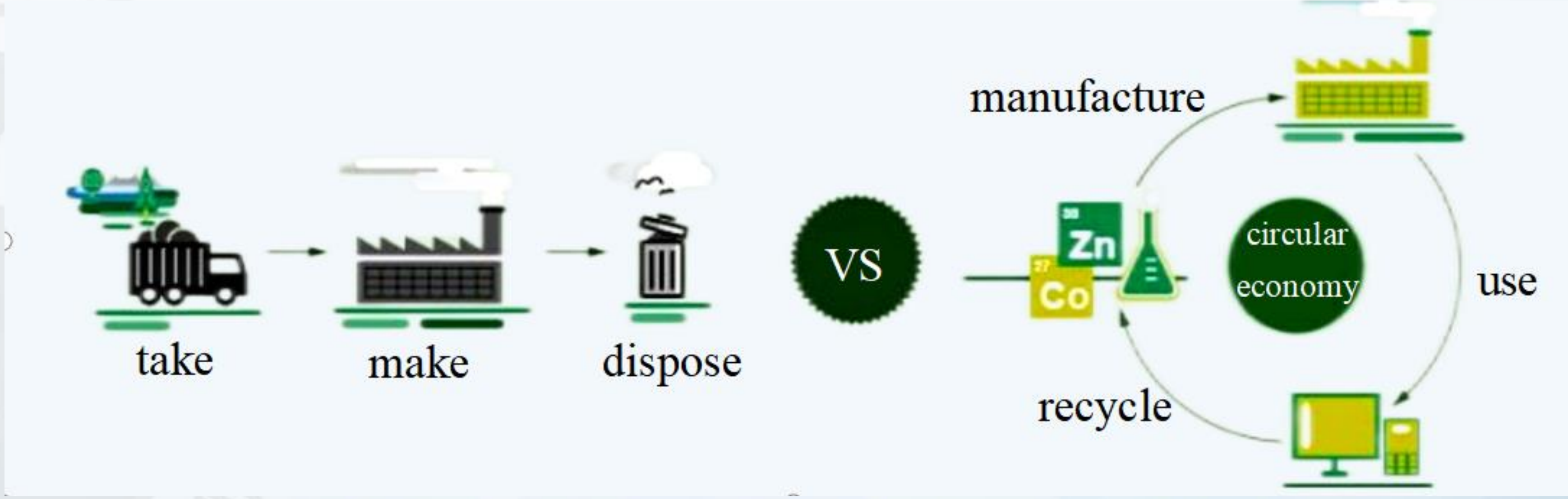
CONTENTS

01 Circular economy and carbon neutrality

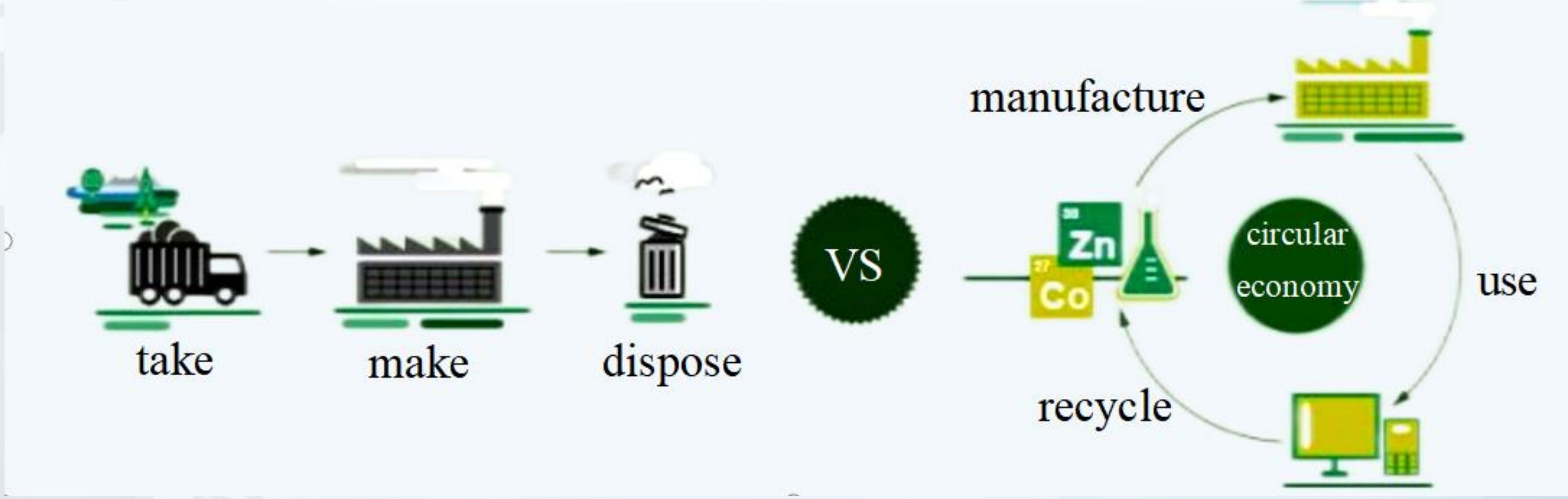
What is circular economy?

A circular economy (also referred to as "circularity") is an economic system aimed at minimizing waste and maintaining the value of products, materials and resources for as long as possible. As opposed to a linear, “take-make-dispose” model in which natural resources are extracted as raw materials for making products that are quickly thrown away after use, a circular economy seeks to close the loops of energy and material flows by employing strategies such as reuse, repair, refurbish, remanufacture and recycle.



What is circular economy?

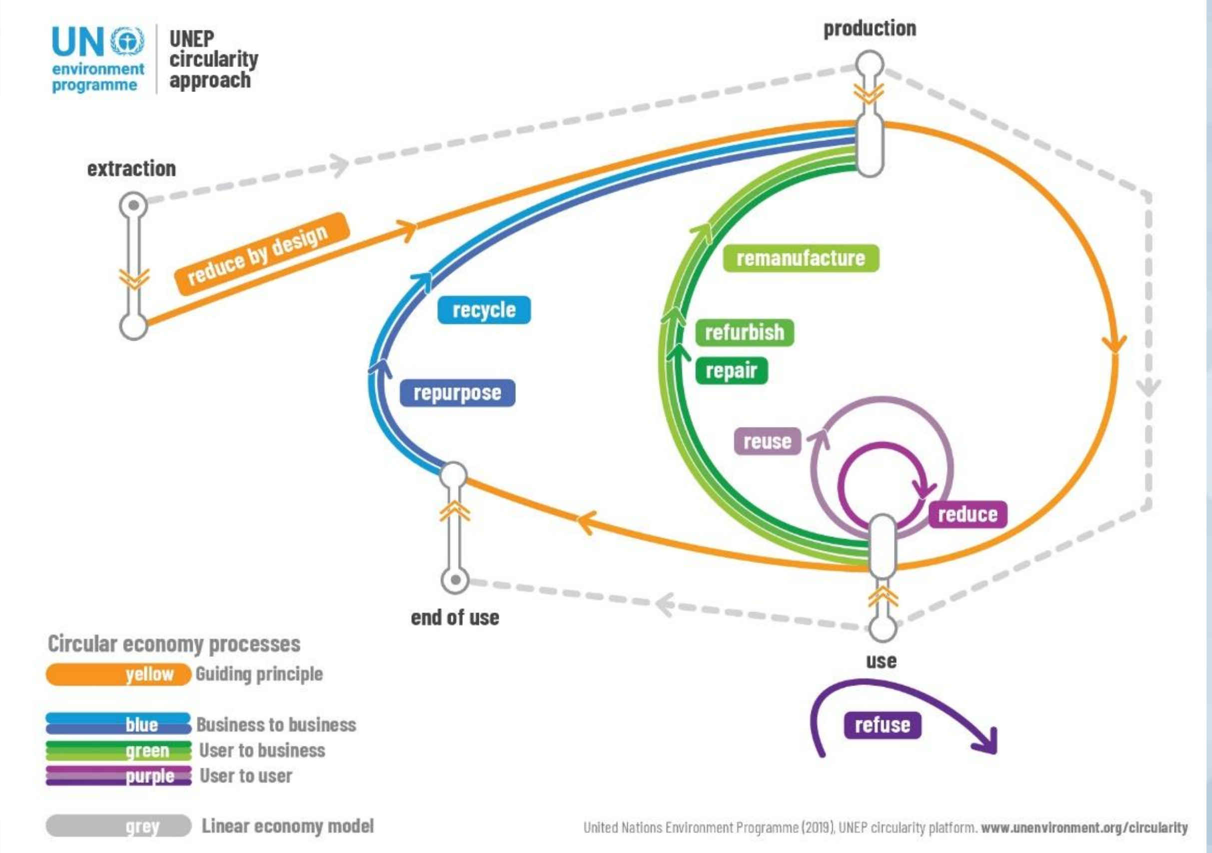
The linear growth path, which depends on the extraction and consumption of finite resources, is inherently unsustainable. A circular economy redefines growth by decoupling economic activities from resource extraction and designing waste out of the system, thus reducing environmental degradation and improving society-wide well-being. The Ellen MacArthur Foundation defines **three guiding principles** of a circular economy, including 1) design out waste and pollution, 2) keep products and materials in use, and 3) regenerate natural systems.



What is circular economy?

The framework of circular economy is structured over the whole life cycle of goods, services and functions across wider social and economic perspectives. A useful framework to understand and approach circularity is the UNEP “9-R” concept which is built upon the following four “value retention loops”

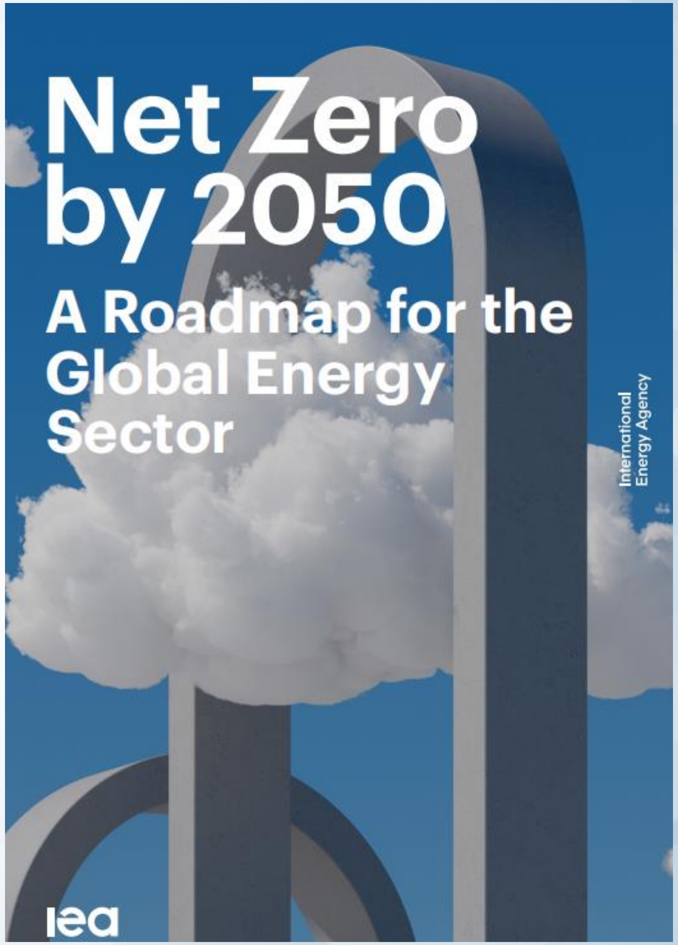
- **From a whole system perspective: Reduce by design**——reducing the amount of material used, particularly raw material, from the earliest stages of design of products and services.
- **From a user-to-user perspective: Refuse, Reduce** and **Re-use**——for instance, consumers saying no to certain products and services, and users choosing to buy less and/or second-hand or using products for a longer time.
- **From a user-to-business intermediary perspective: Repair, Refurbish** and **Remanufacture**.
- **From business-to-business: Repurpose** and **Recycle**——After a product reaches its end of life (EOL), manufacturers may adapt or reprocess the discarded goods, in whole or in part, for another function.



A Circularity approach, UNEP (2019)

What is carbon neutrality?

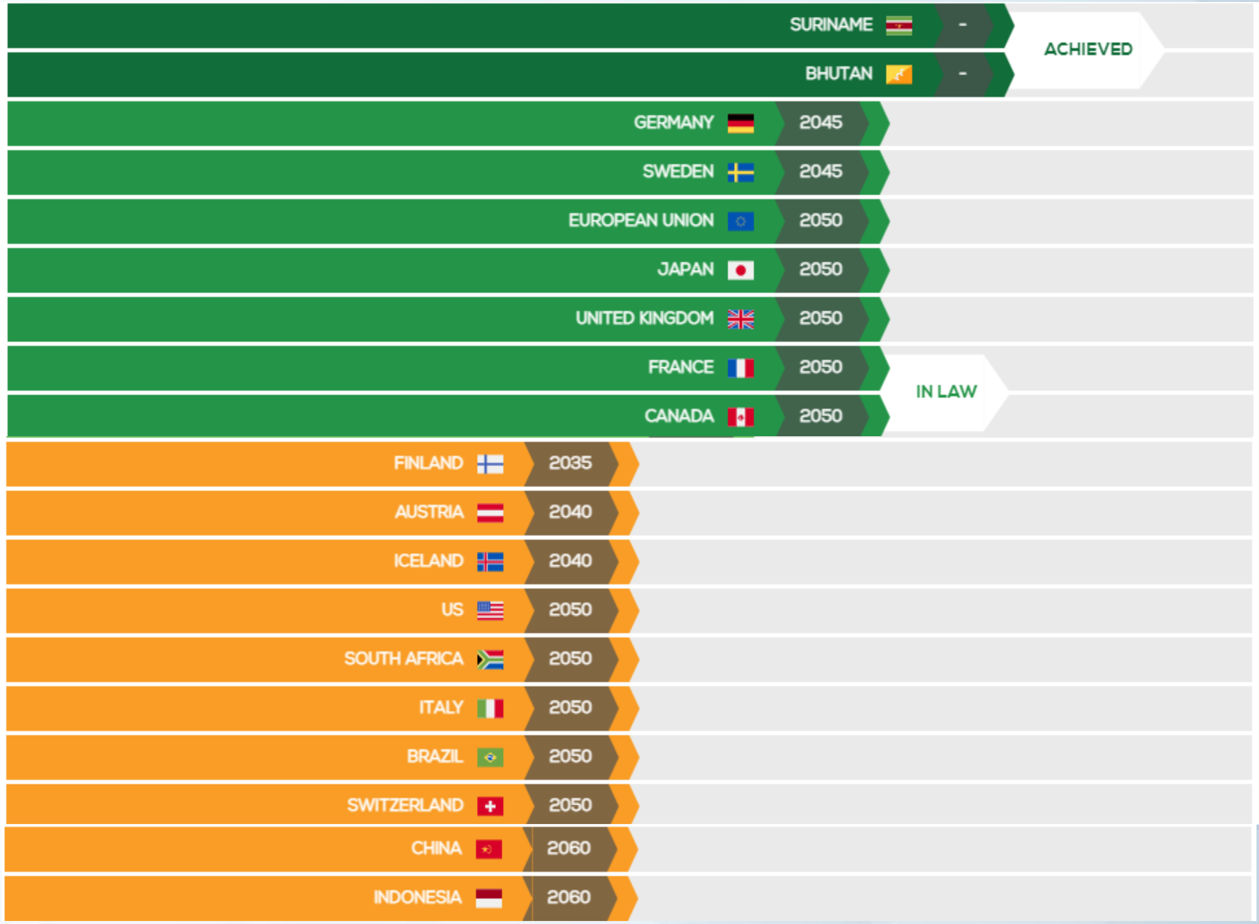
It is international scientific consensus that, in order to prevent the worst climate damages, global net human-caused emissions of carbon dioxide (CO2) need to fall by about 45 percent from 2010 levels by 2030, reaching net zero around 2050. Global warming is proportional to cumulative CO2 emissions, which means that the planet will keep heating for as long as global emissions remain more than zero. This implies that climate damages, caused by global heating, will continue escalating for as long as emissions continue.



Net zero (or carbon neutral, climate neutral) refers to a state in which the greenhouse gases going into the atmosphere are balanced by removal out of the atmosphere. The term net zero is important because – for CO2 at least – this is the state at which global warming stops. To 'go net zero' is to reduce greenhouse gas emissions and/or to ensure that any ongoing emissions are balanced by removals.

What is carbon neutrality?

- The concept of emissions neutrality has gained interest among policy-makers and an increasing number of governments have formulated neutrality targets.
- More than 130 countries have now set or are considering a target of reducing emissions to net zero by mid-century.
- The EU aims to become the first continent that achieves carbon neutrality by 2050.
- The Chinese government promised the world a new goal on September 22, 2020, which is to strive to reach the peak of CO2 emissions by 2030 and achieve carbon neutrality by 2060.

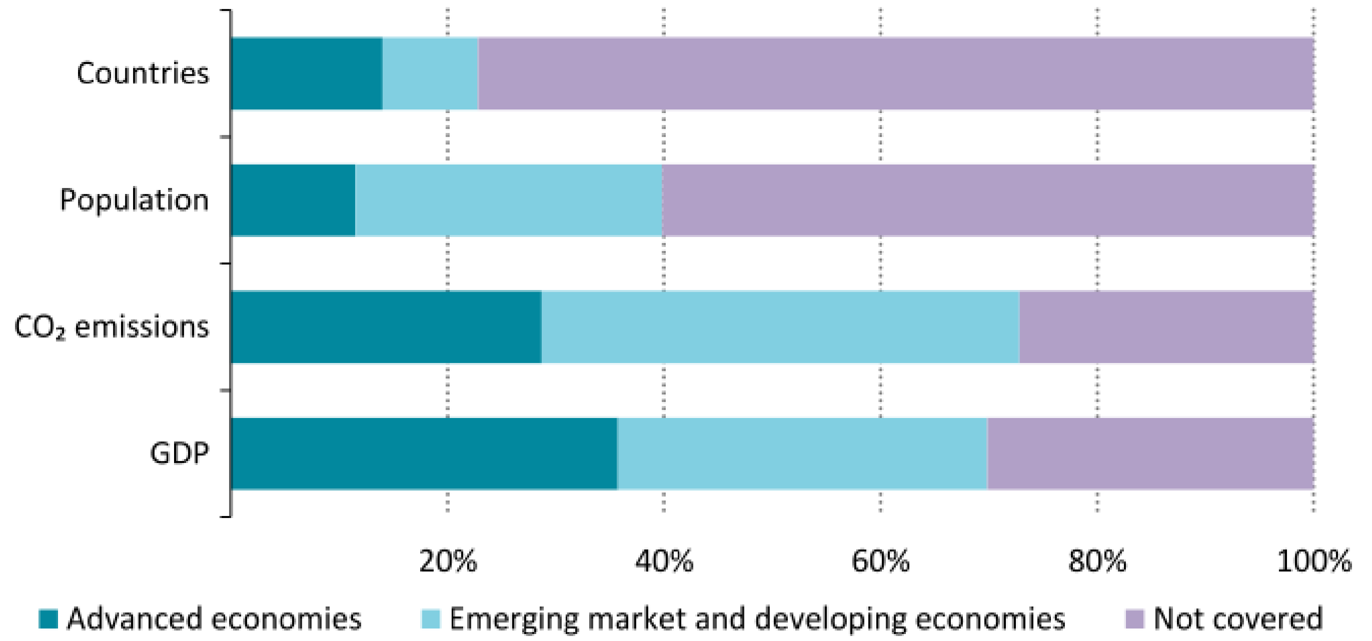


ENERGY & CLIMATE INTELLIGENCE UNIT
NET ZERO EMISSIONS RACE
2021 SCORECARD

(https://eciu.net/netzerotracker)

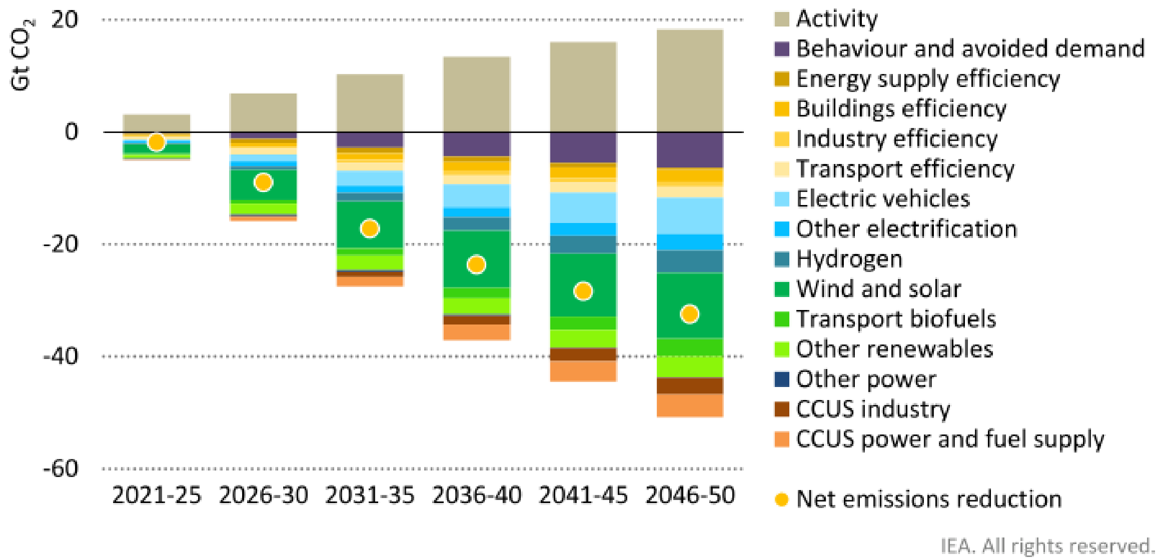
What is carbon neutrality?

Net-zero emissions pledges have been announced by national governments, subnational jurisdictions, coalitions 4 and a large number of corporate entities. As of 23 April 2021, 44 countries and the European Union have pledged to meet a net-zero emissions target: in total they account for around 70% of global CO2 emissions and GDP. Of these, ten countries have made meeting their net zero target a legal obligation, eight are proposing to make it a legal obligation, and the remainder have made their pledges in official policy documents.

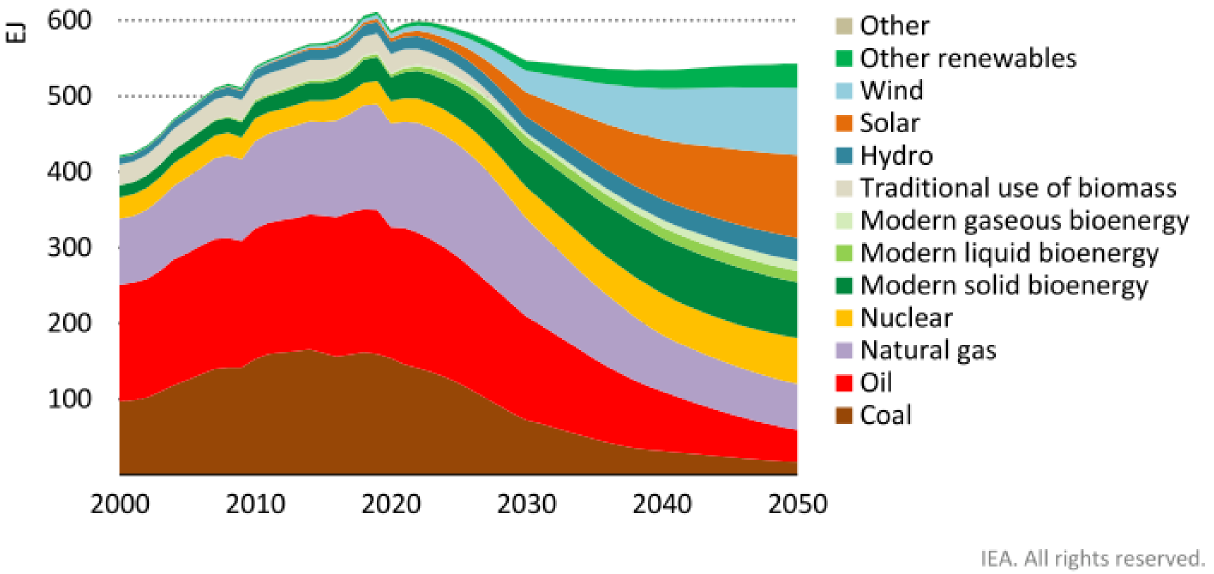


Countries accounting for around 70% of global CO_2 emissions and GDP have set net zero pledges in law, or proposed legislation or in an official policy document

What is carbon neutrality?



Renewables and electrification make the largest contribution to emissions reductions, but a wide range of measures and technologies are needed to achieve net-zero emissions



Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050

Average annual CO2 reductions from 2020 in the net-zero emission

Total energy supply during 2000-2050 in the net-zero emission

Low carbon energy transitions: Renewables and electrification make the largest contribution to emissions reductions, but a wide range of measures and technologies are needed to achieve net-zero emissions (NEZ). Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050.

Circular economy and low carbon energy transition

	Circular economy	Low-carbon energy transition
Definition	Circulating the material and energy flows in an economic system as a closed loop	Transforming energy use into a low-carbon and sustainable pattern
Goals	• Environmental quality • Resource management • Economic prosperity	• Environmental sustainability (especially, climate mitigation) • Energy equity enhancement • Energy security guarantee • Economic prosperity
Principles	• 3R (reduction, reuse, and recycling) or 9R • Life cycle assessment • Stakeholder participation • Economic feasibility	• Energy efficiency and conservation • Low-carbon energy(e.g., renewable energy) • Energy equity and Economic feasibility • Stakeholder participation (particularly, citizens)
Strategies (examples)	• Eco-industrial park • Closed-loop supply chains • Value chains • Sustainable design strategies (SDS)	• Renewable energy deployment • Innovative business models(e.g., energy cooperative initiatives) • Energy demand management(e.g., behavioral changes) • Energy efficiency enhancement(e.g., building retrofit)
Research disciplines (examples)	• Industrial ecology • Material science • Engineering • Environmental policy • Waste management • Economics	• Environmental/resource economics • Energy policy • Electronic engineering • Sociology • Geography • Engineering

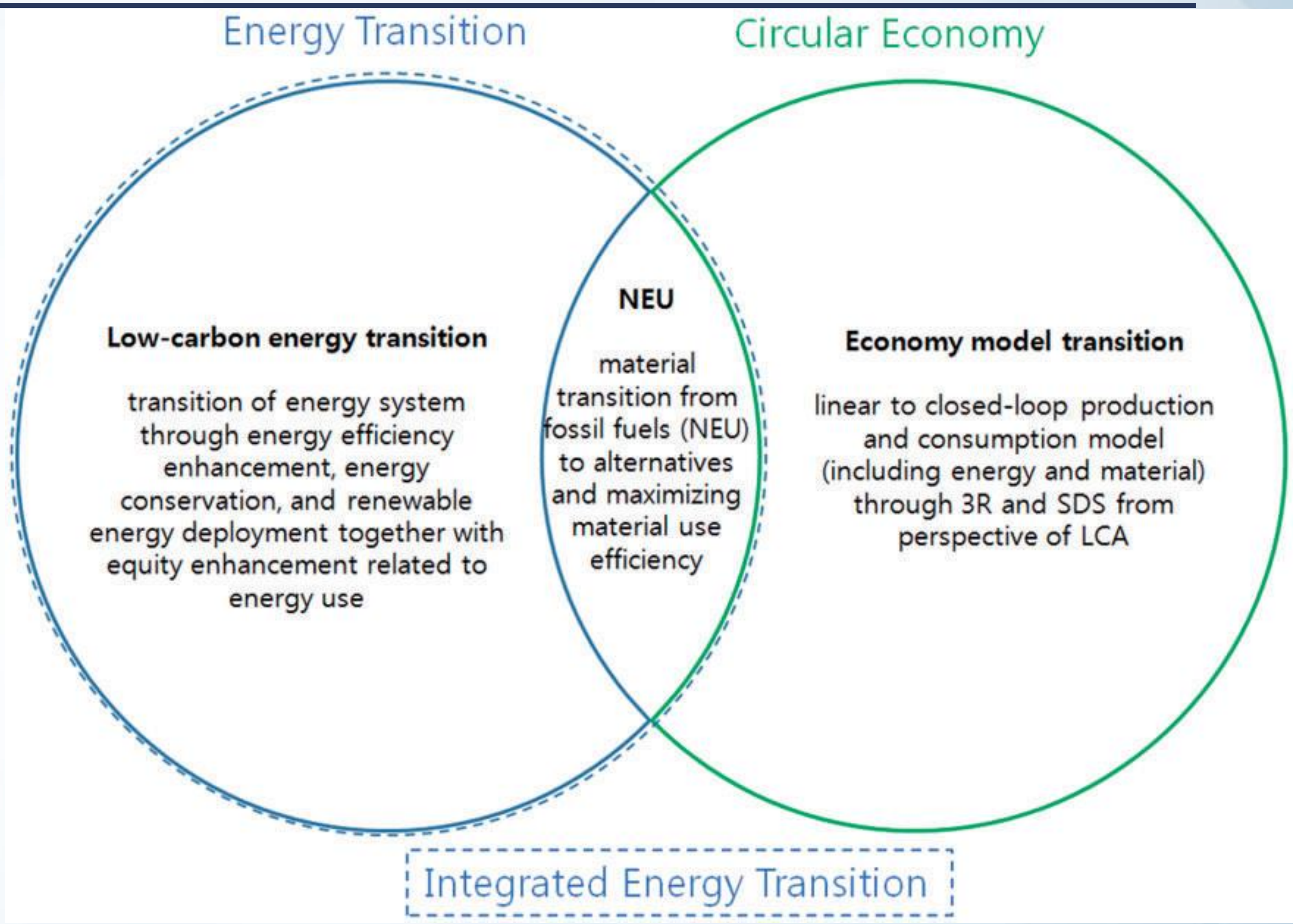
Circular economy and low carbon energy transition

- **Circular economy (CE)**
  — covers materials as well as energy
  — spans resource, environment, and economy dimensions
  — Under CE, effective resource management such as 3R is pursued; these activities are evaluated and applied based on a lifecycle assessment.

- **Low-carbon energy transition (ET)**
  — focuses on energy
  — incorporates social aspects related to energy use in addition to energy security (resource) and environmental sustainability (environment)
  — ET principles emphasize the conditions that enable low-carbon transition: shifting energy sources together with reduced energy consumption. In addition, the transition needs to allow more people to receive modern energy.

Circular economy and low carbon energy transition

- CE and low-carbon ET share common characteristics even though they were promoted by different disciplines. Both concepts concern the environment as well as the economy and aim to reach a sustainable future.
- The figure shows the inter-connection of CE and ET studies, with the nexus of NEU. The reduction of NEU and using environmentally friendly alternatives to NEU in production can promote a CE. At the same time, a low-carbon ET could be promoted by relieving the dependence on fossil fuel NEU.



Schematic diagram of an integrated energy transition model

Material basis of low carbon energy transition

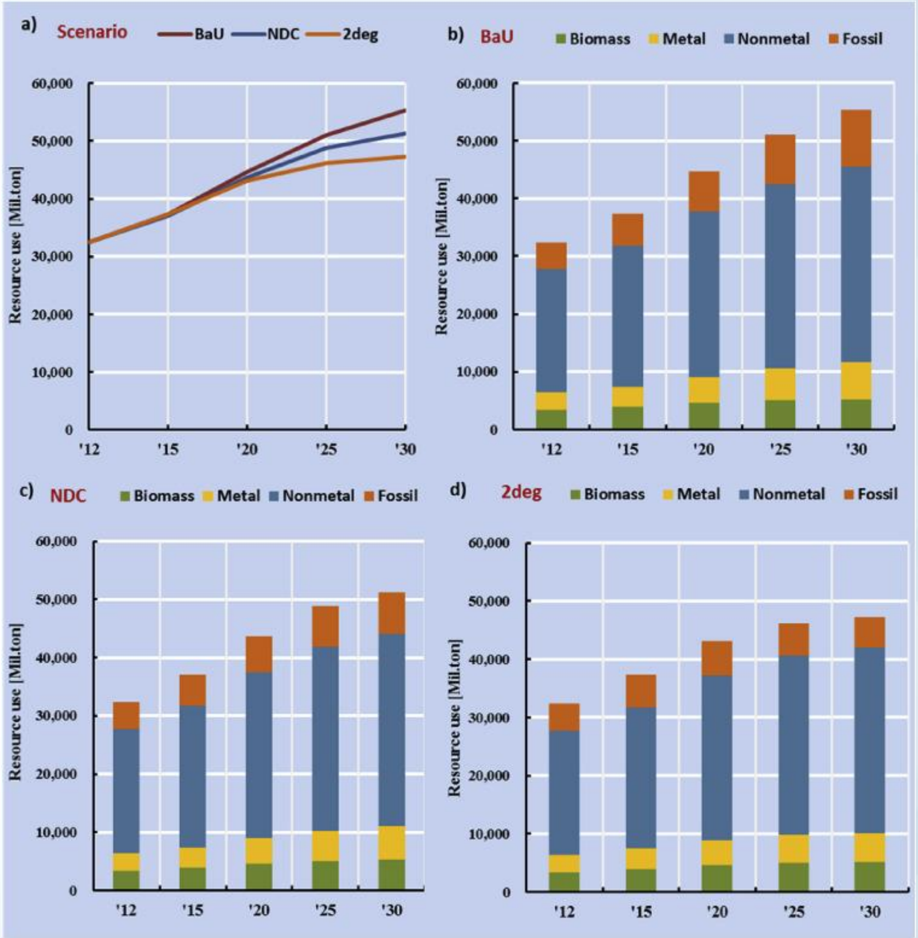
Selected materials used to produce renewable and low energy devices and infrastructures.

Technology	Inventory of materials and commodities
Photovoltaics	Silicon, glass, aluminum, silver, copper, steel, polymers, electronics, indium, gallium, tellurium, germanium, cadmium, zinc
Wind turbines	Steel, copper, aluminum, iron, cement, glass reinforced plastics, plastic resins, dysprosium, neodymium, praseodymium, electronics
Electric vehicles	Steel, aluminum, glass, copper, metal composites, fiberglass, rubber, ceramics and magnets, polymers, lead acid batteries, lithium-ion batteries, electronics
Lithium ion batteries	Steel, iron, nickel, copper, manganese, lithium, cobalt, graphite, zinc, polymers, electronics

Circular economy and low carbon energy transition

- A recent study show co-benefits of circular economy from carbon mitigation in China (https://doi.org/10.1016/j.jclepro.2017.11.070)

- Carbon mitigation could save use of metal ores, nonmetallic minerals, and fossil fuels in China.



Resource consumption of the four material groups in China for three scenarios, 2012–2030

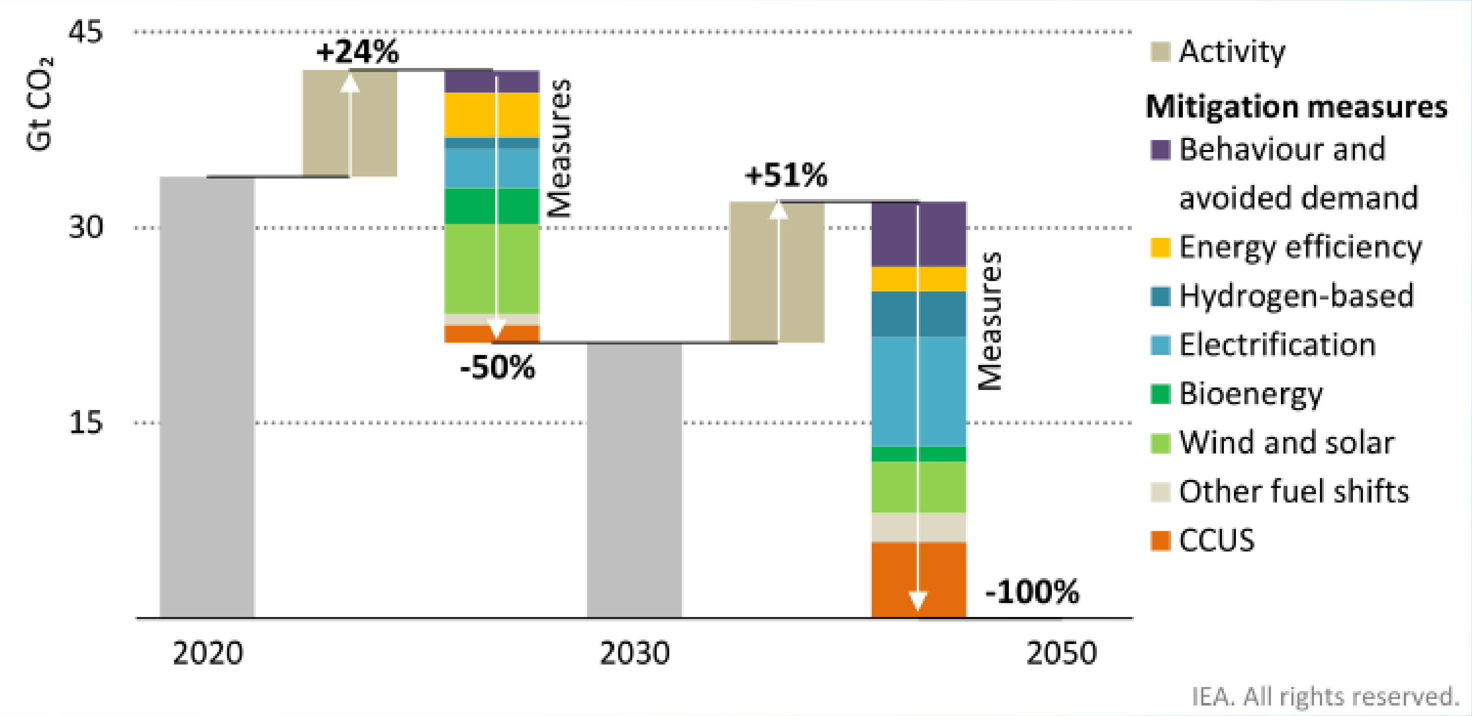
02

Challenges of circular economy from carbon neutrality

Key pillars of decarbonization

- Achieving the rapid reduction in CO2 emissions over the next 30 years in the net-zero emission (NZE) requires a broad range of policy approaches and technologies. The key pillars of decarbonization of the global energy system are **energy efficiency, behavioral changes, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy and carbon capture, utilization and storage (CCUS)**.

- Solar, wind and energy efficiency deliver around half of emissions reductions to 2030 in the NZE, while electrification, CCUS and hydrogen ramp up thereafter.

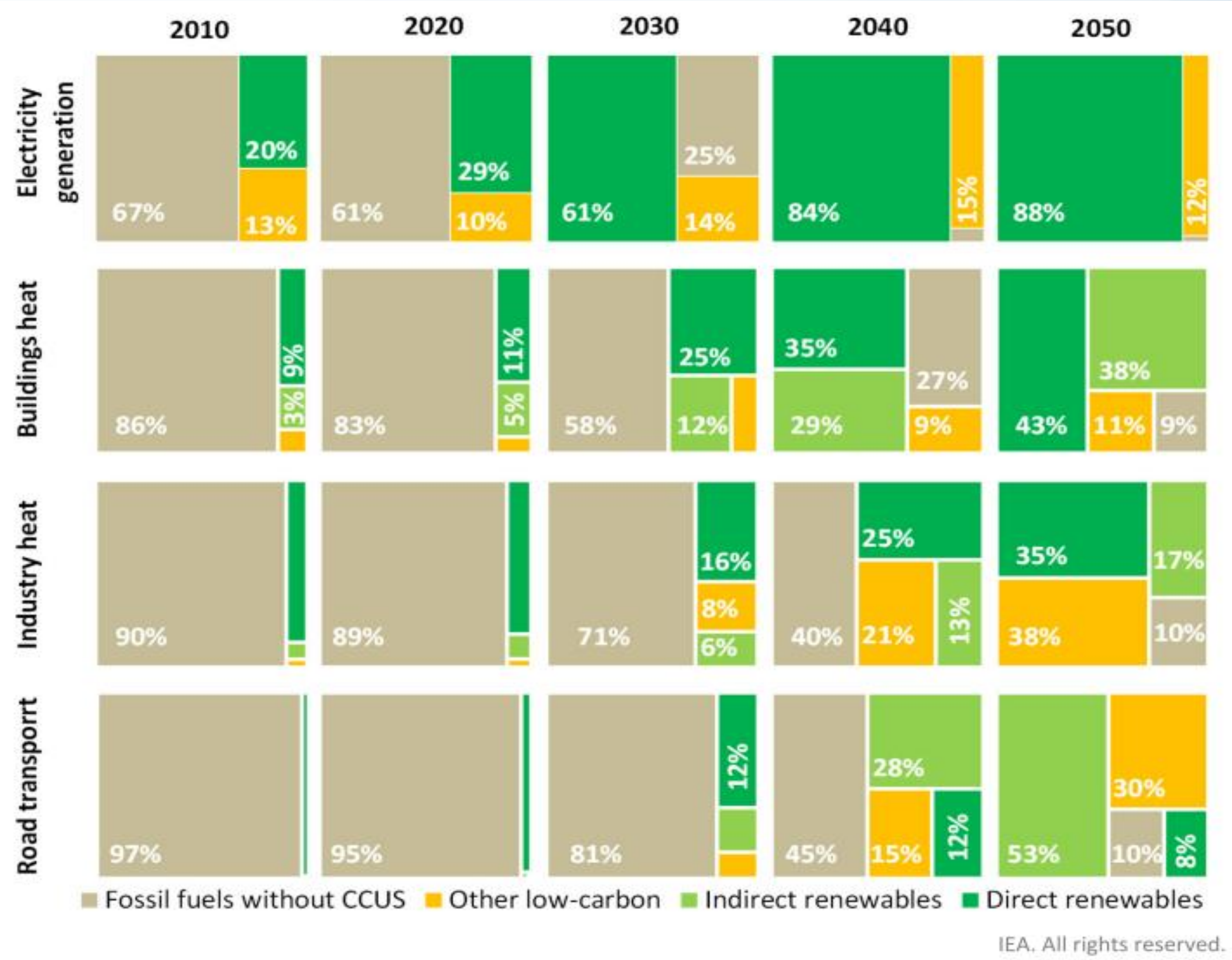


Emissions reductions by mitigation measure in the NZE, 2020-2050

Renewables are central to emissions reductions

- Renewables are central to emissions reductions in electricity, and they make major contributions to cut emissions in buildings, industry and transport both directly and indirectly.

- The share of renewables in total electricity generation globally increases from 29% in 2020 to over 60% in 2030 and to nearly 90% in 2050. To achieve this, annual capacity additions of wind and solar between 2020 and 2050 are five-times higher than the average over the last three years.

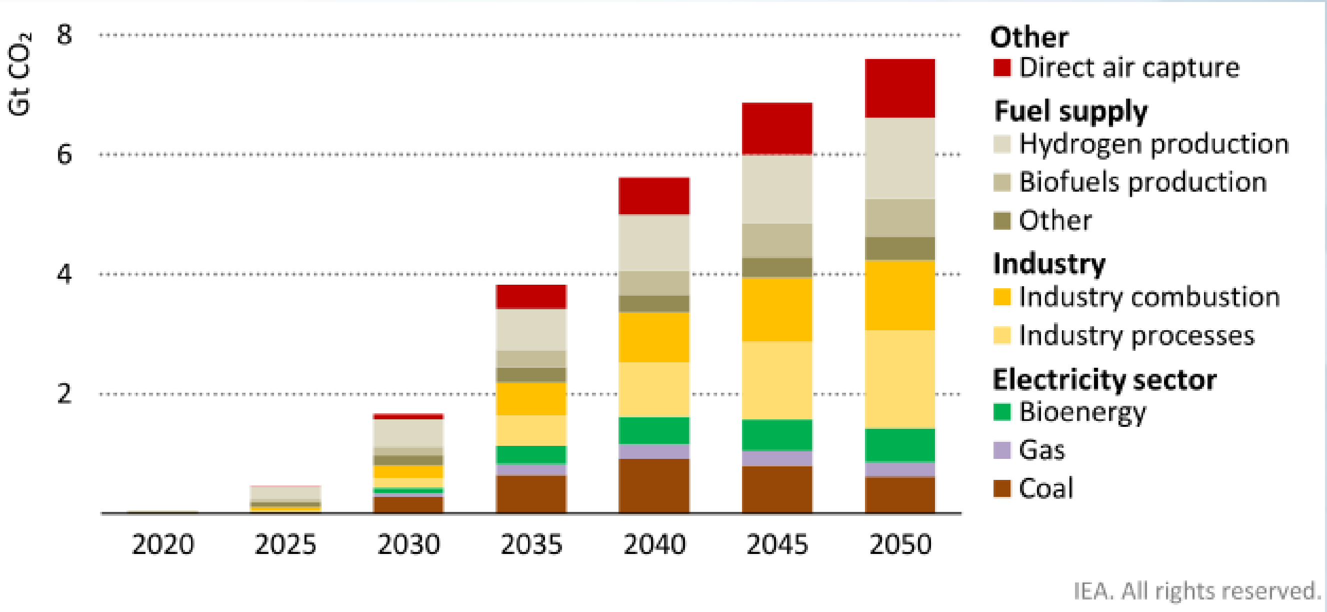


Fuel shares in total energy use in selected applications in the NZE

CCUS are also important

- CCUS can facilitate the transition to net-zero CO2 emissions by: tackling emissions from existing assets; providing a way to address emissions from some of the most challenging sectors; providing a cost-effective pathway to scale up low-carbon hydrogen production rapidly; and allowing for CO2 removal from the atmosphere through BECCS and DACCS.

- By 2050, 7.6 Gt of CO2 is captured per year from a diverse range of sources. A total of 2.4 Gt CO2 is captured from bioenergy use and DAC, of which 1.9 Gt CO2 is permanently stored.



Global CO2 capture by source in the NZE

Renewables requires huge minerals

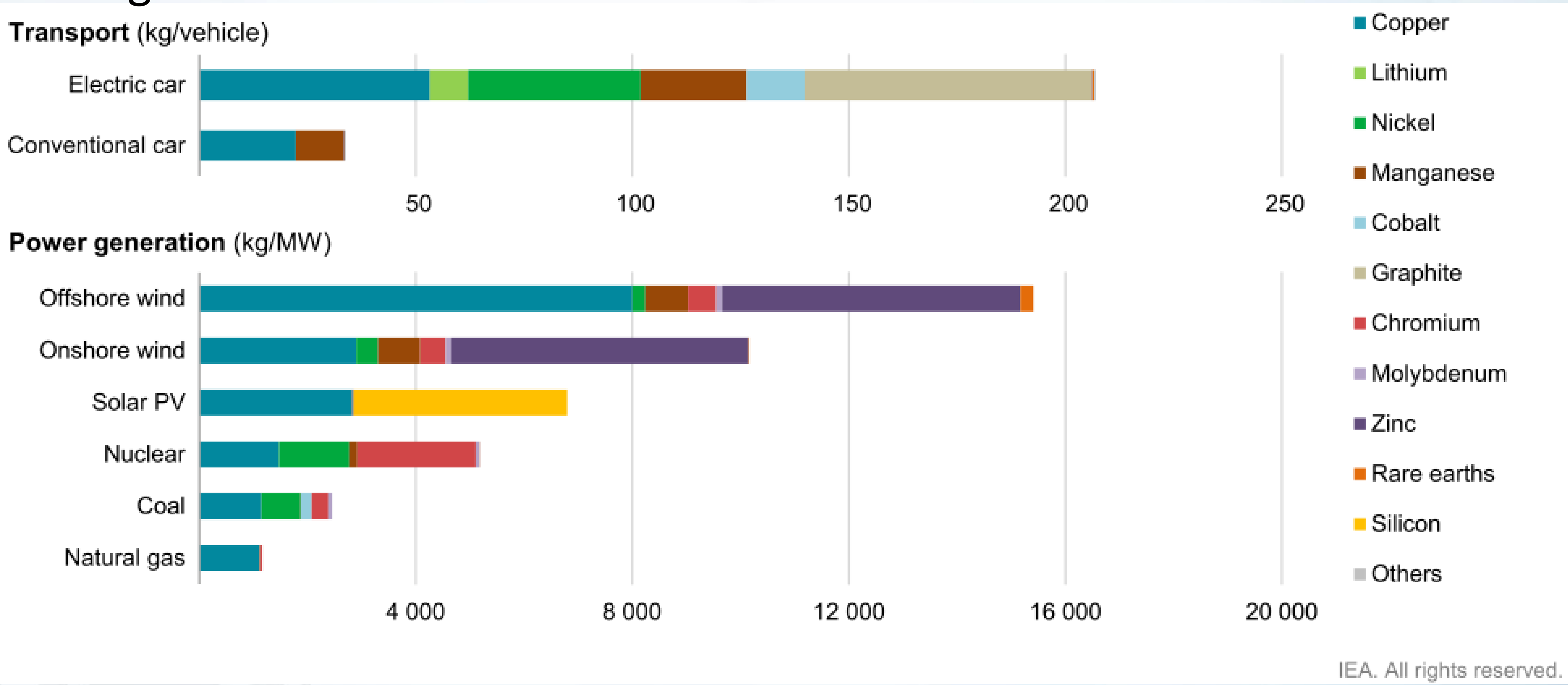
- In the transition to clean energy, critical minerals bring new challenges to energy security.
  - An energy system powered by clean energy technologies differs profoundly from one fueled by traditional hydrocarbon resources. Building solar photovoltaic (PV) plants, wind farms and electric vehicles (EVs) generally requires more minerals than their fossil fuel-based counterparts. A typical electric car requires six times the mineral inputs of a conventional car, and an onshore wind plant requires nine times more mineral resources than a gas-fired power plant. Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables has risen.

  - Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV motors. Electricity networks need a huge amount of copper and aluminum, with copper being a cornerstone for all electricity-related technologies.

  - The shift to a clean energy system is set to drive a huge increase in the requirements for these minerals, meaning that the energy sector is emerging as a major force in mineral markets.

Renewables requires huge minerals

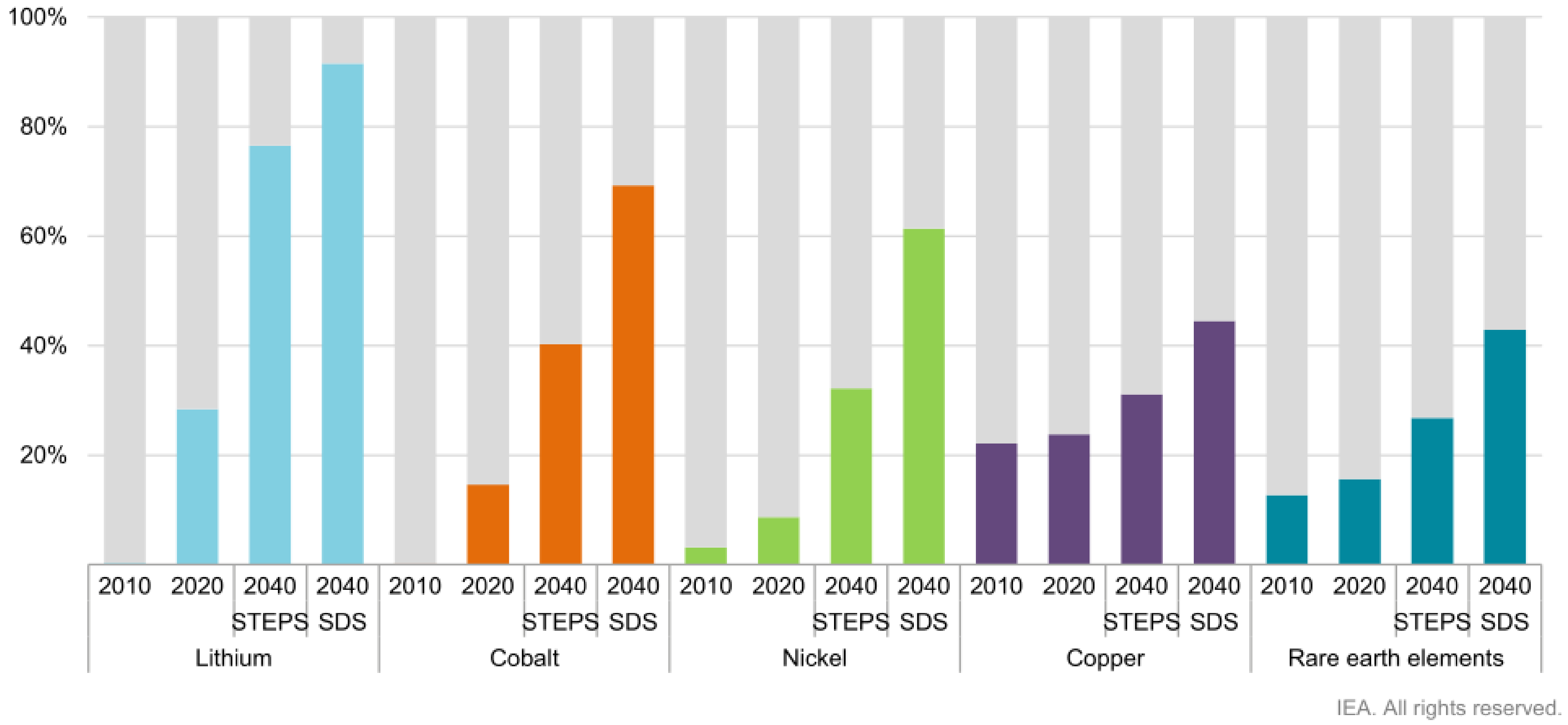
The rapid deployment of clean energy technologies as part of energy transitions implies a significant increase in demand for minerals.



Minerals used in selected clean energy technologies

Renewables requires huge minerals

The energy sector becomes a leading consumer of minerals as energy transitions accelerate



Share of clean energy technologies in total demand for selected minerals

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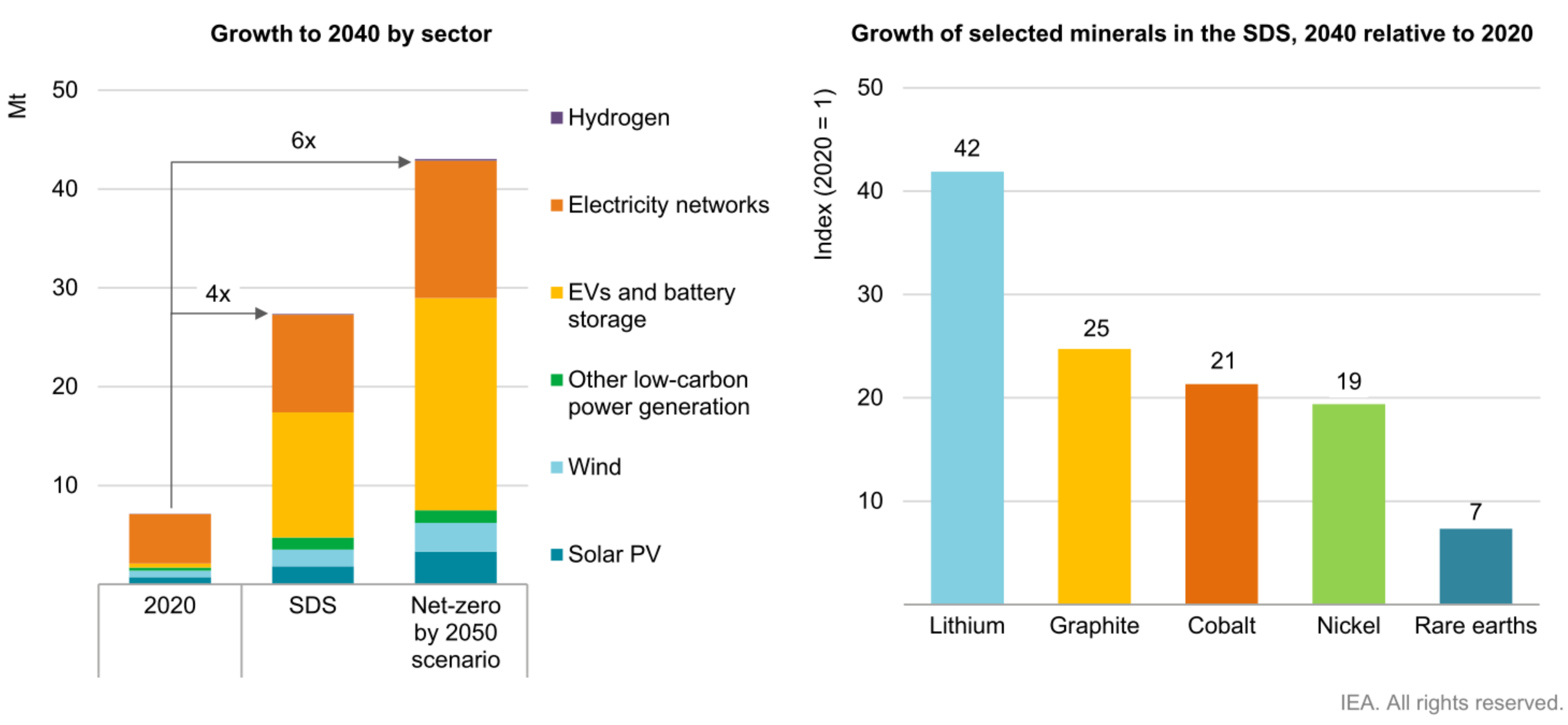
TO BRIDGE BUSINESS WITH TECHNOLOGY, AND TO NURTURE MANAGERIAL TALENTS WITH ADVANCED KNOWLEDGE AND PRACTICAL ABILITY.

Renewables requires huge minerals

Mineral demand for clean energy technologies would rise by at least four times by 2040 to meet climate goals, with particularly high growth for EV-related minerals

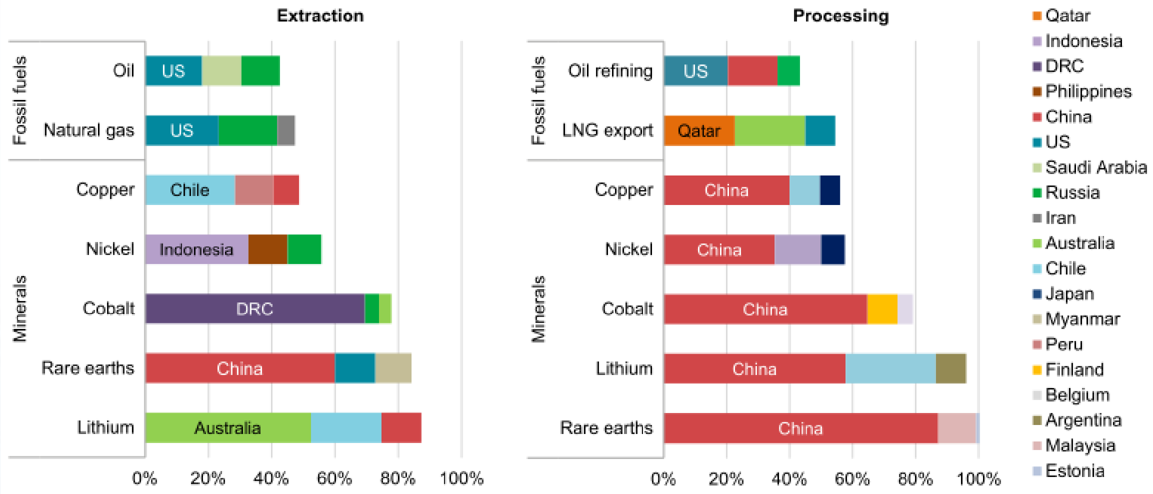


Mineral demand for clean energy technologies by scenario

Challenges from huge increase in mineral consumptions

- **Availability and reliability of supply**

  The prospect of a rapid rise in demand for critical minerals – in most cases well above anything seen previously – poses huge questions about the availability and reliability of supply. Some minerals such as lithium raw material and cobalt are expected to be in surplus in the near term, while lithium chemical, battery-grade nickel and key rare earth elements (e.g. neodymium, dysprosium) might face tight supply in the years ahead. However, looking further ahead in a scenario consistent with climate goals, expected supply from existing mines and projects under construction is estimated to meet only half of projected lithium and cobalt requirements and 80% of copper needs by 2030.



Share of top three producing countries in production of selected minerals and fossil fuels, 2019

Challenges from huge increase in mineral consumptions

- **Growing scrutiny of environmental and social performance**

  Production and processing of mineral resources gives rise to a variety of environmental and social issues that, if poorly managed, can harm local communities and disrupt supply. Consumers and investors are increasingly calling for companies to source minerals that are sustainably and responsibly produced. Without efforts to improve environmental and social performance, it may be challenging for consumers to exclude poor-performing minerals as there may not be sufficient quantities of high-performing minerals to meet demand.

- **Higher exposure to climate risks**

  Mining assets are exposed to growing climate risks. Copper and lithium are particularly vulnerable to water stress given their high water requirements. Over 50% of today's lithium and copper production is concentrated in areas with high water stress levels. Several major producing regions such as Australia, China, and Africa are also subject to extreme heat or flooding, which pose greater challenges in ensuring reliable and sustainable supplies.

Challenges from huge increase in mineral consumptions

A recent study show that critical rare-earth (RE) elements mismatch global wind-power ambitions (https://doi.org/10.1016/j.oneear.2020.06.009)

- 11- to 26-fold expansion of RE supply is needed for meeting global wind-power targets.
- The global RE requirement is estimated at 460–902 Gg in 2021–2050.
- European wind-power development faces the highest risk of RE shortage.
- Material recycling and efficiency, production expansion, and technical innovation are promising for alleviating RE supply shortages in the long term.
- However, the existing global RE supply structure, along with the intensifying geopolitical and environmental constraints, could inhibit the rapid expansion of wind power, which calls for global cooperation to foster a sustainable and responsible RE supply chain.

Circular economy could help

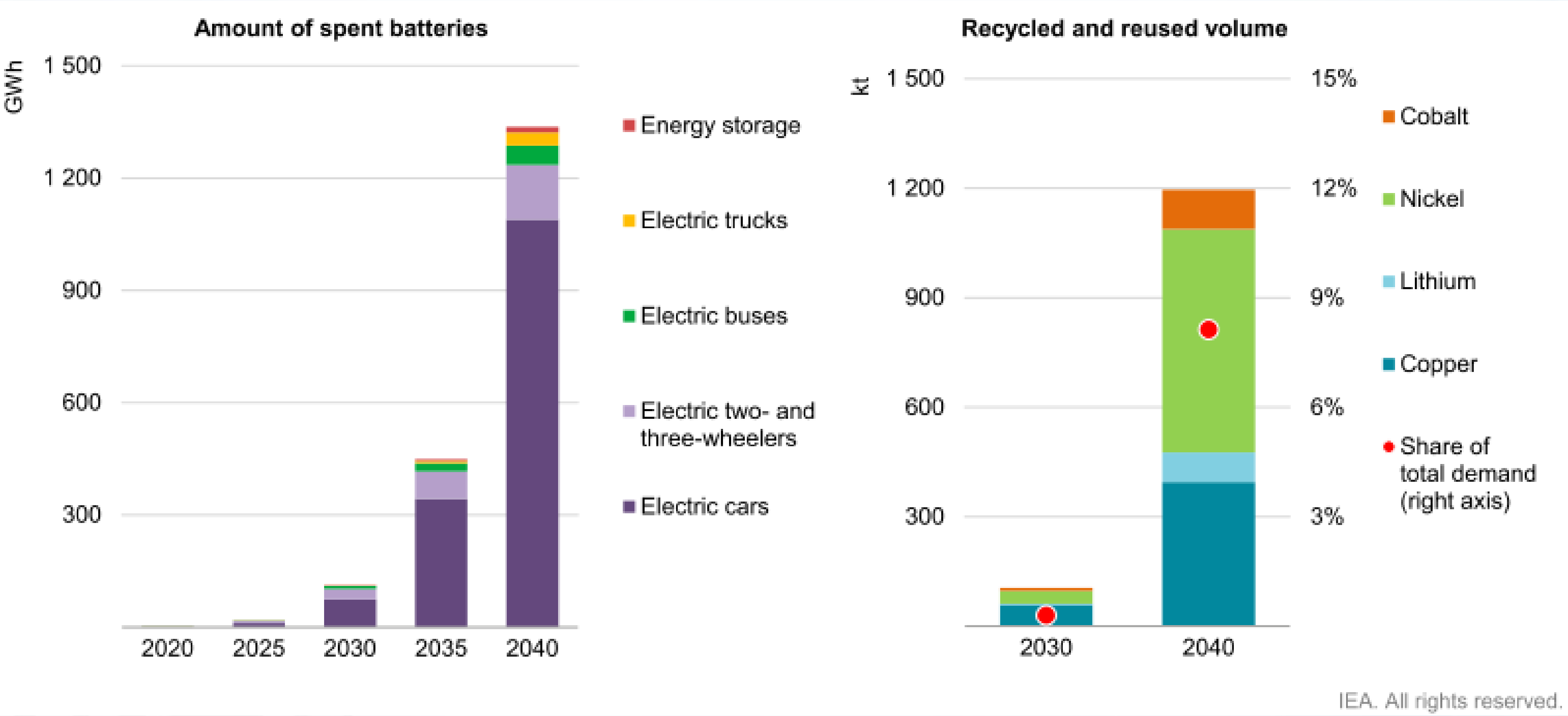
- **Reducing material intensity via technological innovation**

  Reducing material intensity and encouraging material substitution via technology innovation can also play major roles in alleviating strains on supply, while also reducing costs. For example, 40-50% reductions in the use of silver and silicon in solar cells over the past decade have enabled a spectacular rise in solar PV deployment. Innovation in production technologies can also unlock sizeable new supplies. Emerging technologies, such as direct lithium extraction or enhanced metal recovery from waste streams or low-grade ores, offer the potential for a step change in future supply volumes.

- **Recycling relieves the pressure on primary supply**

  The amount of spent EV batteries reaching the end of their first life is expected to surge after 2030, at a moment of continued rapid growth in mineral demand. By 2040, recycled quantities of copper, lithium, nickel and cobalt from spent batteries could reduce combined primary supply requirements for these minerals by around 10%.

Circular economy could help



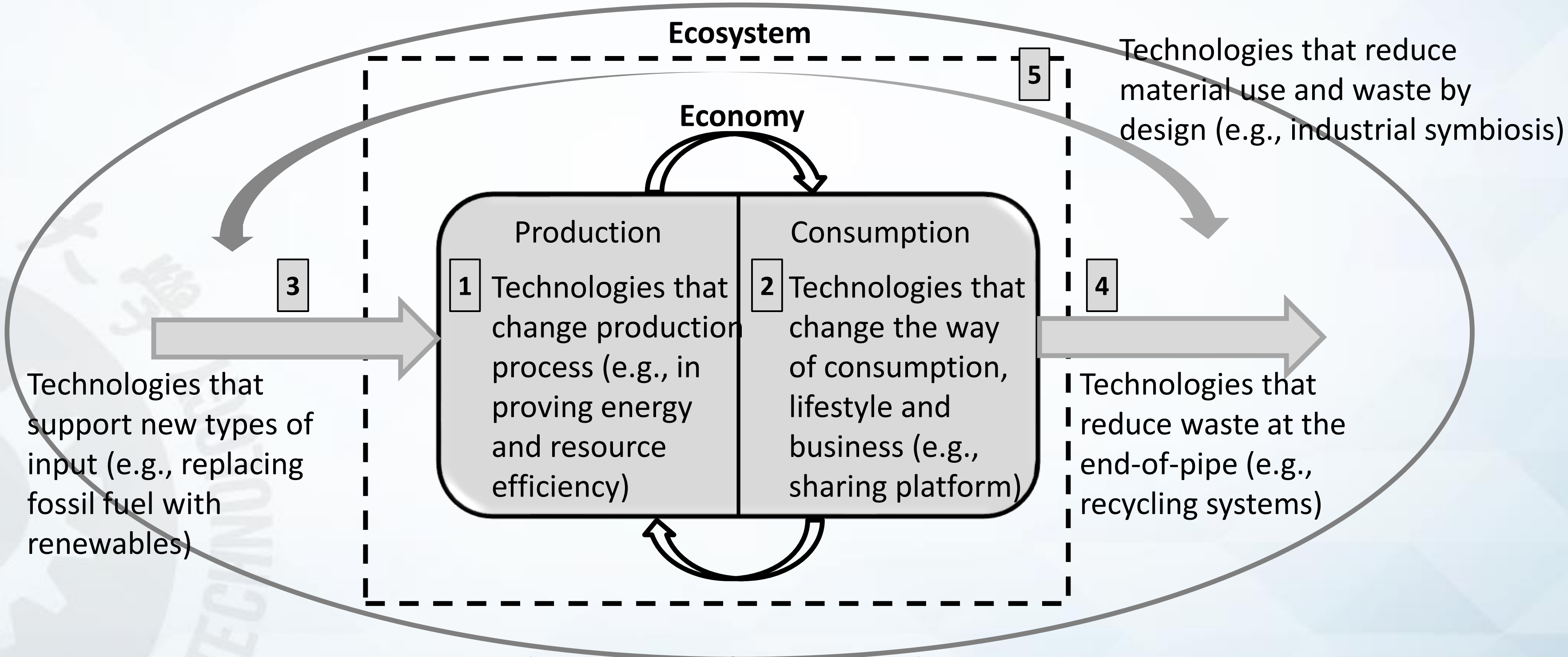
Amount of spent lithium-ion batteries from EVs and storage and recycled and reused minerals from batteries

03

The role of technology

Positive effect of technology

- In the context of circular economy, technologies can improve the value retention of materials and products and reduce waste. The figure shows how various types of green technologies can be integrated into economic processes to promote circularity.

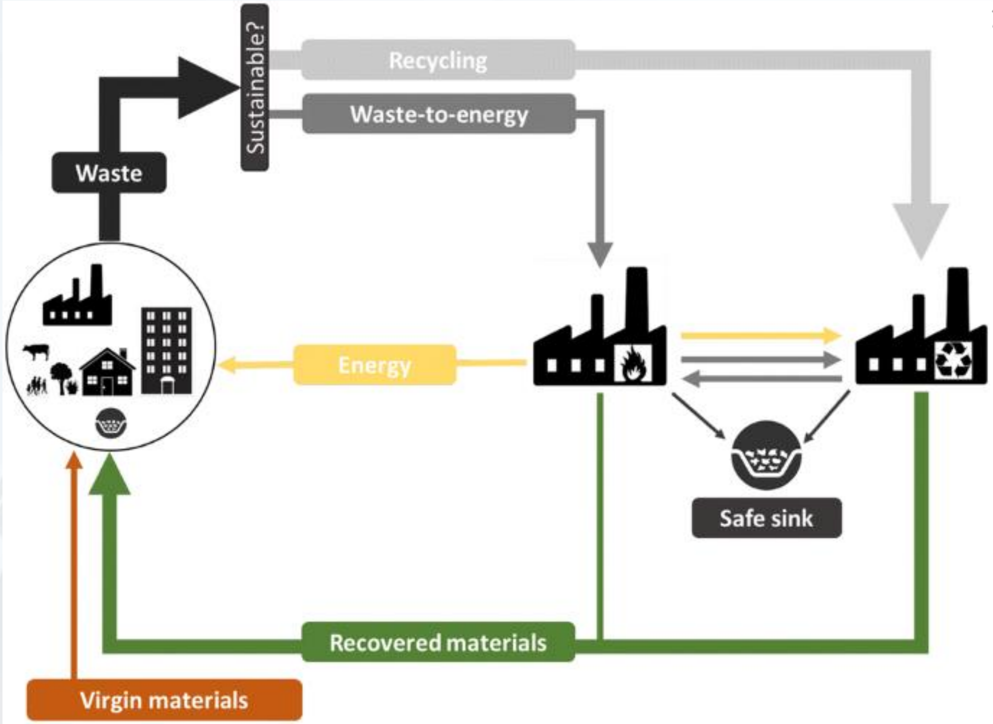


Green technologies for a circular economy

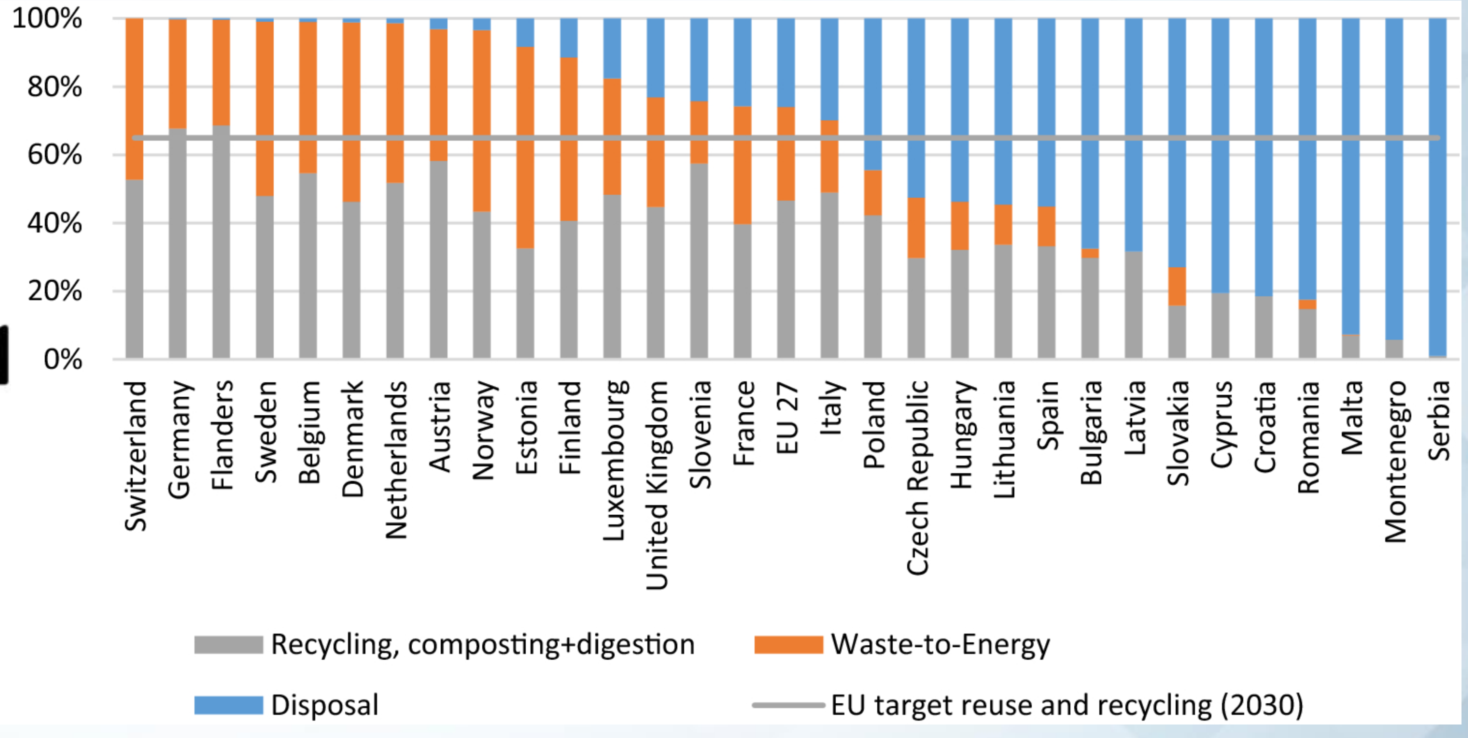
Positive effect of technology

- Technology designed for enhancing circularity holds the potential to resolve sustainability challenges. Here is why:
  - Technology could promote the decoupling of economic growth from resource use.
  - Technology - particularly digital innovations - can disrupt existing linear value chains and promote the decoupling of economic growth from over-consumption.
  - Technology, when applied at scale can enable a systemic transition to a circular economy.
- While the circular technologies and business models present important opportunities, it is imperative to put in place an enabling policy and investment framework to support the update of technological innovation.

The role of waste-to-energy technology



waste-to-energy framework



MSW management in the different EU member states in 2015

The role of waste-to-energy technology

- A recent research reviews the role of conventional waste-to-energy, i.e. incineration of (mainly) municipal solid waste with energy recovery, in the circular economy (https://doi.org/10.1007/s10098-019-01686-0). Results show:
  - Although waste-to-energy figures on a lower level in the European waste hierarchy than recycling, it plays, from an overall sustainability point of view, an essential, complementary and facilitating role within the circular economy.
  - First of all, waste-to-energy combusts (or should combust) only waste that is non-recyclable for economic, technical or environmental reasons. This way waste-to-energy is compatible with recycling and only competes with landfill, which is lower in the waste hierarchy.
  - Furthermore, waste-to-energy keeps material cycles, and ultimately the environment and humans largely free from toxic substances.
  - Finally, waste-to-energy allows recovery of both energy and materials from non-recyclable waste and hence contributes to keeping materials in circulation.

Be careful about technology – the Circular Economy Rebound

- Technology has played a vital role in achieving economic and social prosperity. However, the increased productivity and the over-exploitation and -consumption of resources that come with technological advancements, have led to some unfavorable environmental outcomes, such as resource scarcity, habitat loss and pollution, which put long-term sustainable development at risk.

- **Energy Efficiency Rebound:** In energy efficiency literature, the rebound effect describes the phenomenon where increased efficiency makes consumption of some good (e.g., energy or transportation) relatively cheaper and, as a result, people consume more of it. This increased use decreases the environmental benefit of the efficiency increase, and can even lead to “backfire,” where the increase in use is proportionally larger than the efficiency increase, leading to higher net impacts.

- **Circular Economy Rebound:** Circular economy activities can increase overall production, which can partially or fully offset their benefits. As there is a strong parallel in this respect to energy efficiency rebound, which is termed as ‘Circular Economy Rebound’.

Be careful about technology – the Circular Economy Rebound

- Energy rebound occurs when increases in use-phase efficiency are offset by increased use; circular economy rebound occurs when increases in production or consumption efficiency are offset by increased levels of production and consumption.

- **Broader circular economy rebound**:
  - Increased refillable bottle use, for instance, could lead to increased production and operation of refilling stations;
  - Increased emphasis on recycling could lead consumers to purchase more disposable products, believing they can erase their impact at the recycling bin;
  - Availability of cheaper materials attributed to increased recycling may change consumer tastes (e.g., the perceived value of Apple products made from aluminum rather than plastic);
  - Repair occupations that have systematically disappeared over the past century may start to re-emerge with unpredictable effects on employment, affluence, immigration, and overall consumption levels and patterns.

Be careful about technology – the Circular Economy Rebound

- **Mechanism of circular economy rebound** (https://doi.org/10.1111/jiec.12545). There are at least two general mechanisms by which secondary production can lead to rebound. The first has to do with the substitutability of secondary goods; the second has to do with the effect of secondary goods on market prices.

  - **Rebound Attributed to Insufficient Substitutability.** Secondary goods may be insufficient substitutes for primary goods because they are of inferior quality or are otherwise less desirable to users. This means that recycled plastics, papers, and some metals are likely to be produced in addition to, rather than instead of, primary materials, and the potential benefits of recycling will be reduced.

  - **Rebound Attributed to Price Effects.** Increased secondary production activity impacts prices. In order to entice buyers to purchase lower-grade materials, sellers offer them at a discount relative to primary materials. As a result of increased paper and plastic recycling, more goods are now produced, sold, and used.

Be careful about technology – the Circular Economy Rebound

- **Avoiding Circular Economy Rebound**
  - First, it is necessary that circular economy activities produce products and materials that truly are substitutes for primary production alternatives.
  - Second, it is necessary that circular economy activities either have no effect on or decrease aggregate demand for goods. This is to say that they either must target areas with fairly satiable demand (i.e., markets where buyers' price sensitivity is low), or they must ensure that increased secondary production does not significantly affect overall prices.
  - Third, if the first two conditions are met, it is also necessary that the circular economy activity actually draws consumers away from primary production. In other words, substitution from primary to secondary goods must actually occur.

Case study of rebound effect

- **Do sectoral material efficiency improvements add up to greenhouse gas emissions reduction on an economy-wide level?** (https://doi.org/10.1111/jiec.13138)

The study focuses on three material categories: iron and steel, non-ferrous metals, and non-metallic minerals for construction. Results show that ME improvements in iron and steel production and consumption processes can contribute to reducing GHG emissions, but only by a small amount. Eco-design and novel technologies that use less materials in general, can also contribute to GHG emission reduction. Such mitigation potential is especially large for the construction of buildings and infrastructure due to the sector's massive use of non-metallic minerals with a large climate impact (e.g., cement).

However, process efficiency and reduced demand for the three materials do not necessarily lead to reduced GHG emissions on an economy-wide level and can even result in increased GHG emissions due to a rebound effect in other sectors and other processes.

Case study of rebound effect

- **Material recycling would not always reduce the material we landfill.** (https://doi.org/10.1111/jiec.12808)

Proponents of material recycling typically point to two environmental benefits: disposal (landfill/incinerator) reduction and primary production displacement. However, a recent research mathematically demonstrate that, without displacement, recycling can delay but not prevent any existing end-of-life material from reaching final disposal. The only way to reduce the amount of material ultimately landfilled or incinerated is to produce less in the first place; material that is not made needs not be disposed.

Recycling has the potential to reduce the amount of material reaching end of life solely by reducing primary production. Therefore, the “dual benefits” of recycling are in fact one, and the environmental benefit of material recycling rests in its potential to displace primary production. However, displacement of primary production from increased recycling is driven by market forces and is not guaranteed.

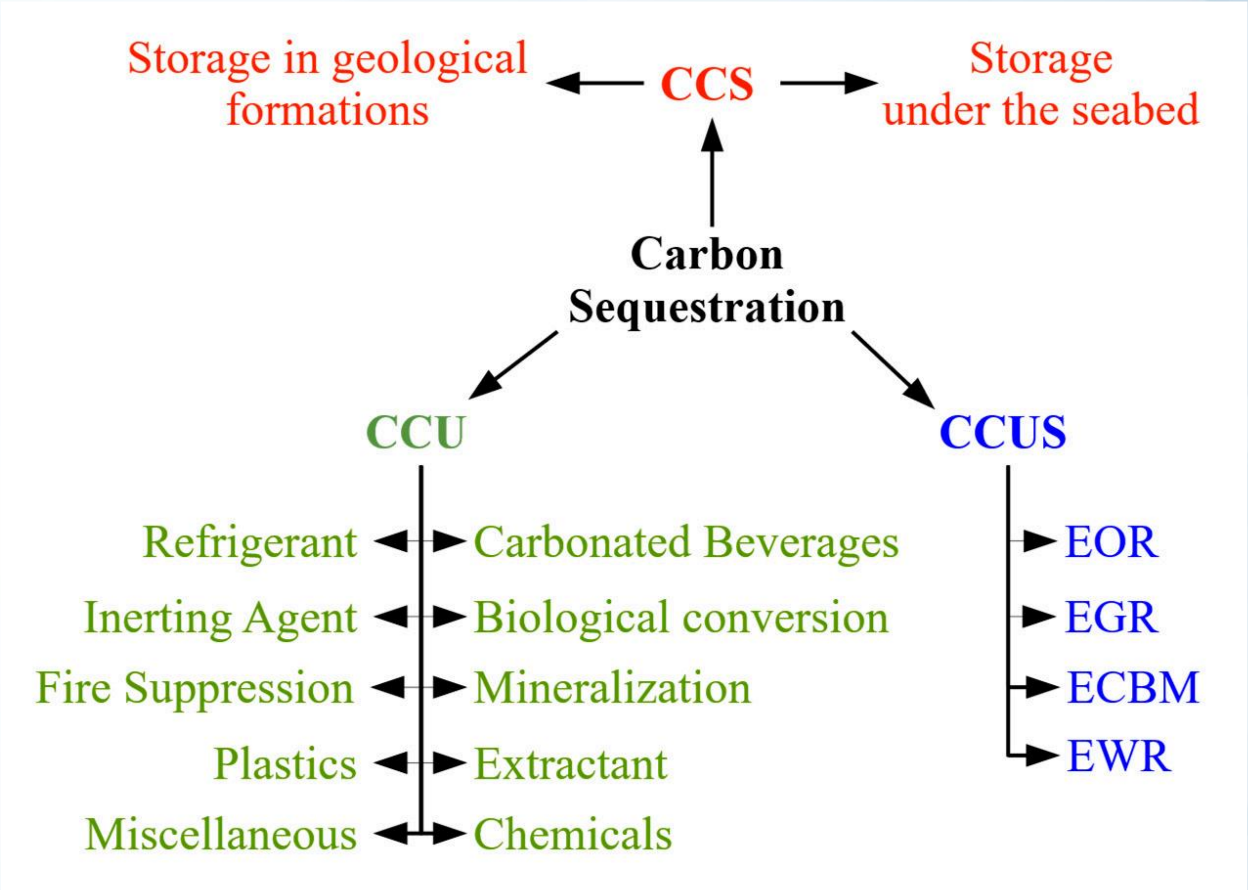
04

CO2 in the transition to a circular economy

Carbon sequestration technologies

- The ‘net’ in net zero is important because it will be very difficult to reduce all emissions to zero on the timescale needed. As well as deep and widespread cuts in emissions, we need carbon sequestration.

- CO_2 sequestration is a cluster of technologies, which can be divided into three groups: carbon capture and storage (CCS); carbon capture, utilization, and storage (CCUS); and carbon capture and utilization (CCU).



Cluster of carbon sequestration technologies

Pathways for the utilization of carbon dioxide

Ten pathways

(https://doi.org/10.1038/s41586-019-1681-6)

(1) CO_2-based chemical products, including polymers;

(2) CO_2-based fuels;

(3) microalgae fuels and other microalgae products;

(4) concrete building materials;

(5) CO_2 enhanced oil recovery (CO_2-EOR);

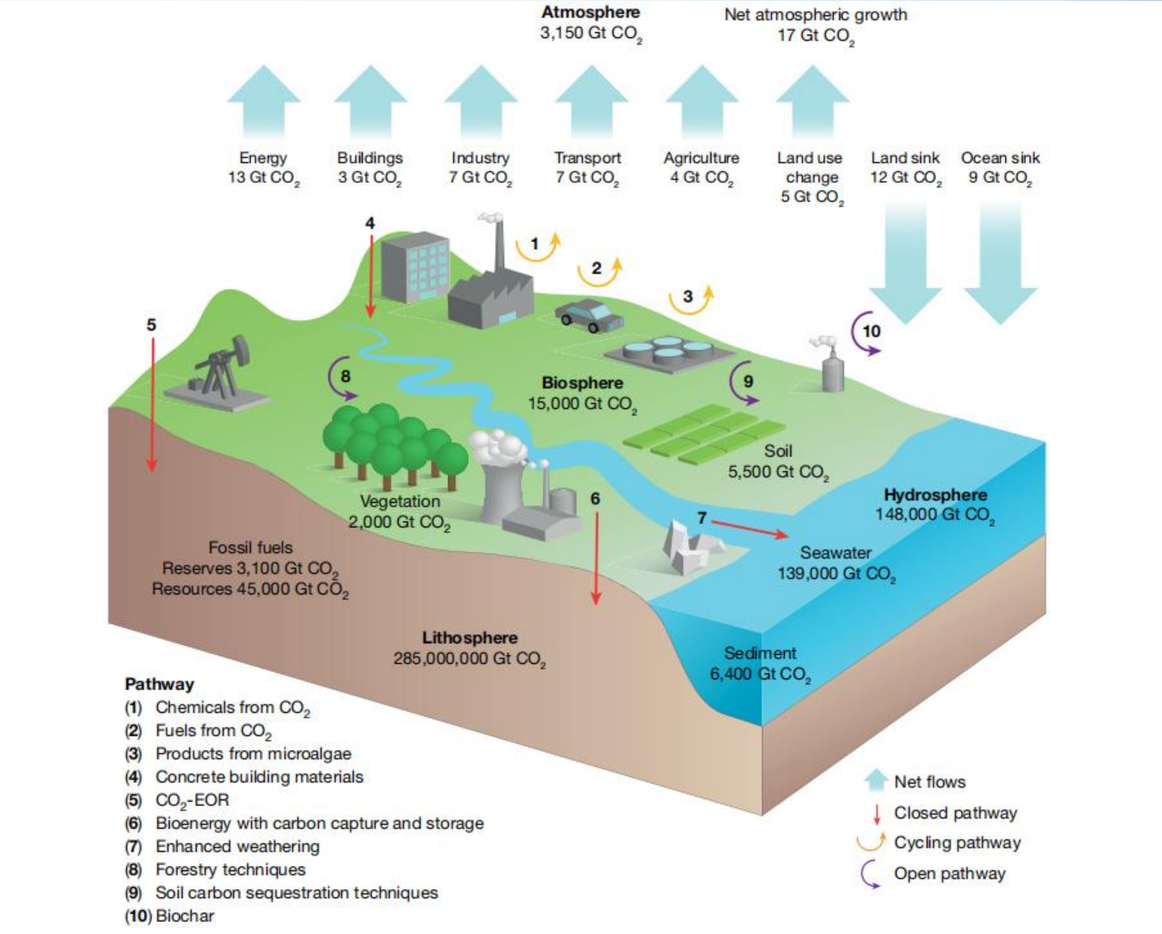
(6) bioenergy with carbon capture and storage (BECCS);

(7) enhanced weathering;

(8) forestry techniques, includingafforestation/reforestation, forest management and wood products;

(9) land management via soil carbon sequestration techniques;

(10) biochar.



Stocks and net flows of CO2 including potential utilization and removal pathways

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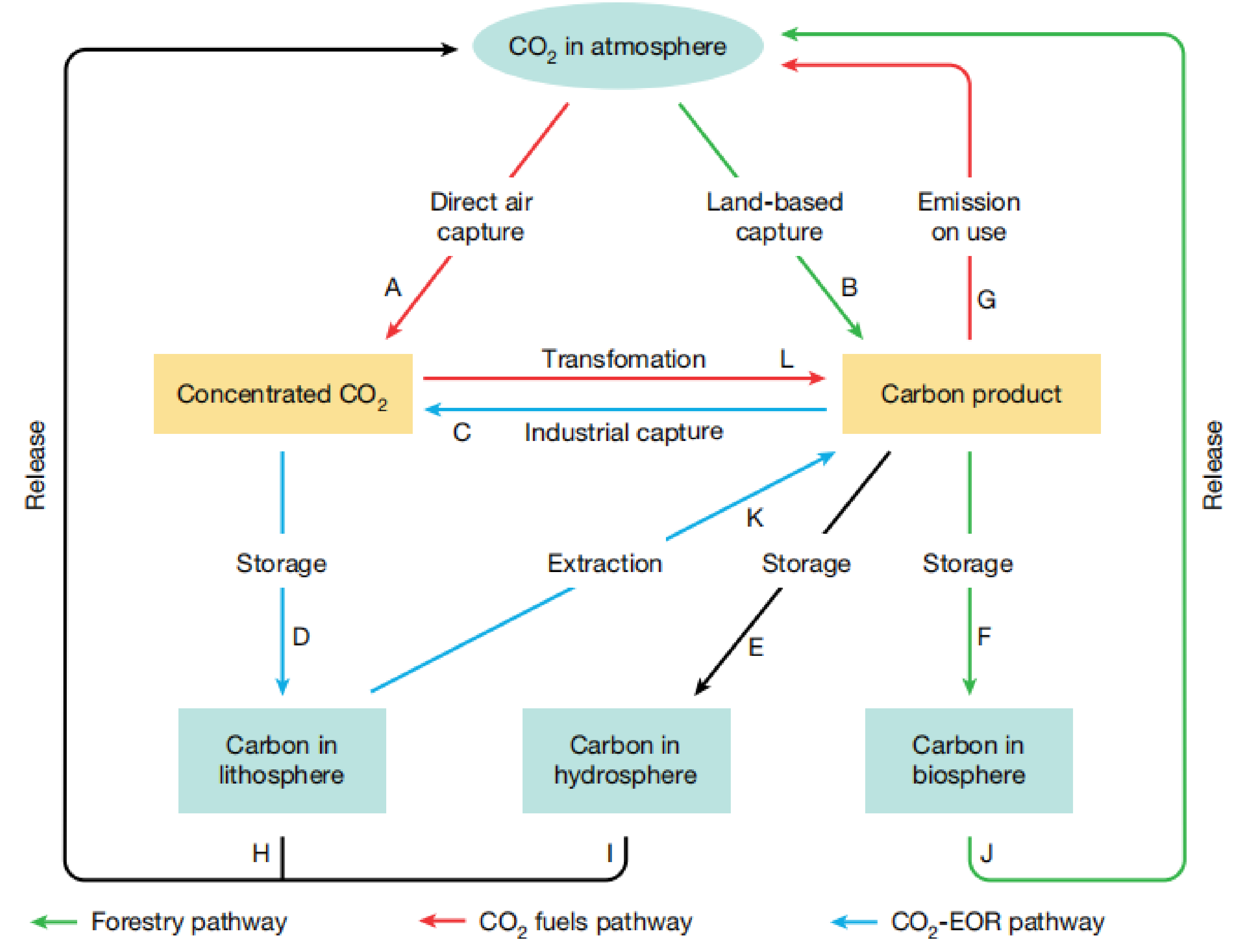
Pathways for the utilization of carbon dioxide

Pathway	Removal and/or capture	Utilization product	Storage and likelihood of release (high/low)	Emission on usefor release during storage
(1) Chemicals from CO_2	Catalytic chemical conversion of CO_2 from flue gas or other sources into chemical products	CO_2-derived platform chemicals such as methanol, urea and plastics	Various chemicals (days/decades) – high	Hydrolysis or decomposition
(2) Fuels from CO_2	Catalytic hydrogenation processes to convert CO_2 from flue gas or other sources into fuels	CO_2-derived fuels such as methanol, methane and Fischer–Tropsch_x0002_derived fuels	Various fuels (weeks/months) – high	Combustion
(3) Products from microalgae	Uptake of CO_2 from the atmosphere or other sources by microalgae biomass	Biofuels, biomass, or bioproducts such as aquaculture feed	Various products (weeks/months) – high	Combustion (fuel) or consumption (bioproduct)
(4) Concrete building materials	Mineralization of CO_2 from flue gas or other sources into industrial waste materials, and CO_2 curing of concrete	Carbonated aggregates or concrete products	Carbonates (centuries) – low	Extreme acid conditions
(5) CO_2-EOR	Injection of CO_2 from flue gas or other sources into oil reservoirs	Oil	Geological sequestration (millennia) – low[e]	n.a.
(6) Bioenergy with carbon capture and storage (BECCS)	Growth of plant biomass	Bioenergy crop biomass	Geological sequestration (millennia) – low[e]	n.a.
(7) Enhanced weathering	Mineralization of atmospheric CO_2 via the application of pulverized silicate rock to cropland, grassland and forests	Agricultural crop biomass	Aqueous carbonate (centuries) – low	Extreme acidic conditions
(8) Forestry techniques	Growth of woody biomass via afforestation, reforestation or sustainable forest management	Standing biomass, wood products	Standing forests and long-lived wood products (decades to centuries) – high	Disturbance, combustion or decomposition
(9) Soil carbon sequestration techniques	Increase in soil organic carbon content via various land management practices	Agricultural crop biomass	Soil organic carbon (years to decades) – high	Disturbance or decomposition
(10) Biochar	Growth of plant biomass for pyrolysis and application of char to soils	Agricultural or bioenergy crop biomass	Black carbon (years to decades) – high	Decomposition

Pathways for the utilization of carbon dioxide

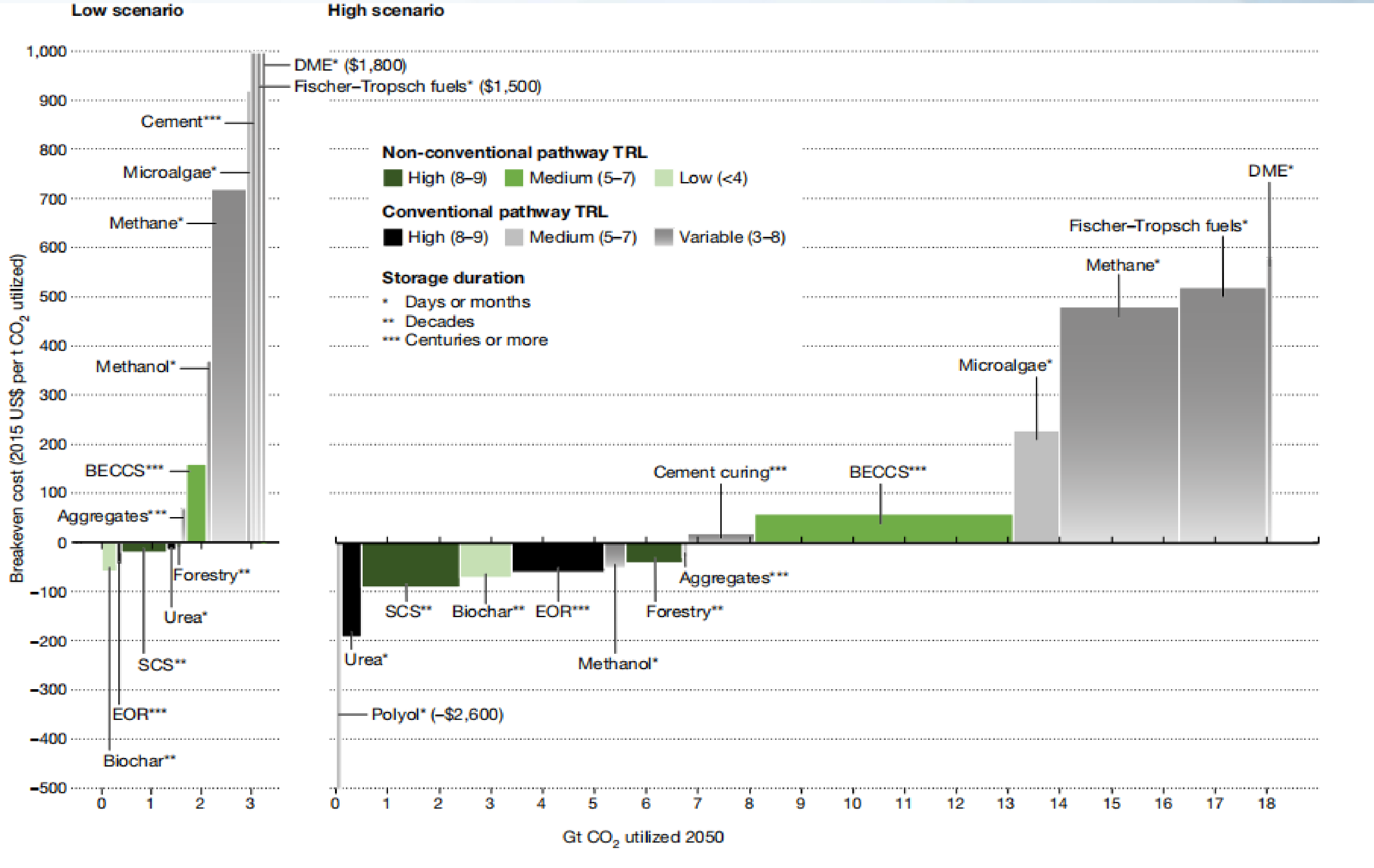
The flow of CO2 through the different utilization pathways can be represented by a combination of different steps (labels A to L). Utilization pathways often (but not always) involve removal (A or B) and storage (D, E or F); however, the permanence of CO2 storage varies greatly from one utilization pathway to another, with storage timeframes ranging from days to millennia.



Carbon dioxide utilization and removal cycle

Pathways for the utilization of carbon dioxide

The breakeven cost is the incentive, measured in 2015 US$ per tonne of CO_2, that is required to make the pathway economic. Negative breakeven costs indicate that the pathway is already profitable, without any incentive to utilize CO_2 (such as a tax on CO_2 emissions in cases in which utilization avoids emissions, or a subsidy for CO_2 removed from the atmosphere in the case in which utilization removes CO_2).



Estimated CO_2 utilization potential and breakeven cost of different sub-pathways in low and high scenarios

CO_2 in the transition to a circular economy

- The development of sequestration technologies has been associated with the transition from a linear to a circular economy in several studies. Despite this, a significant aspect of this transition has been missed—the development of waste management and waste processing technologies, which are also typical for many other industries. This is important because in the framework of CCS projects, CO_2 is nothing more than a waste that needs to be effectively “stored”; however this is not the case in CCUS and CCU.

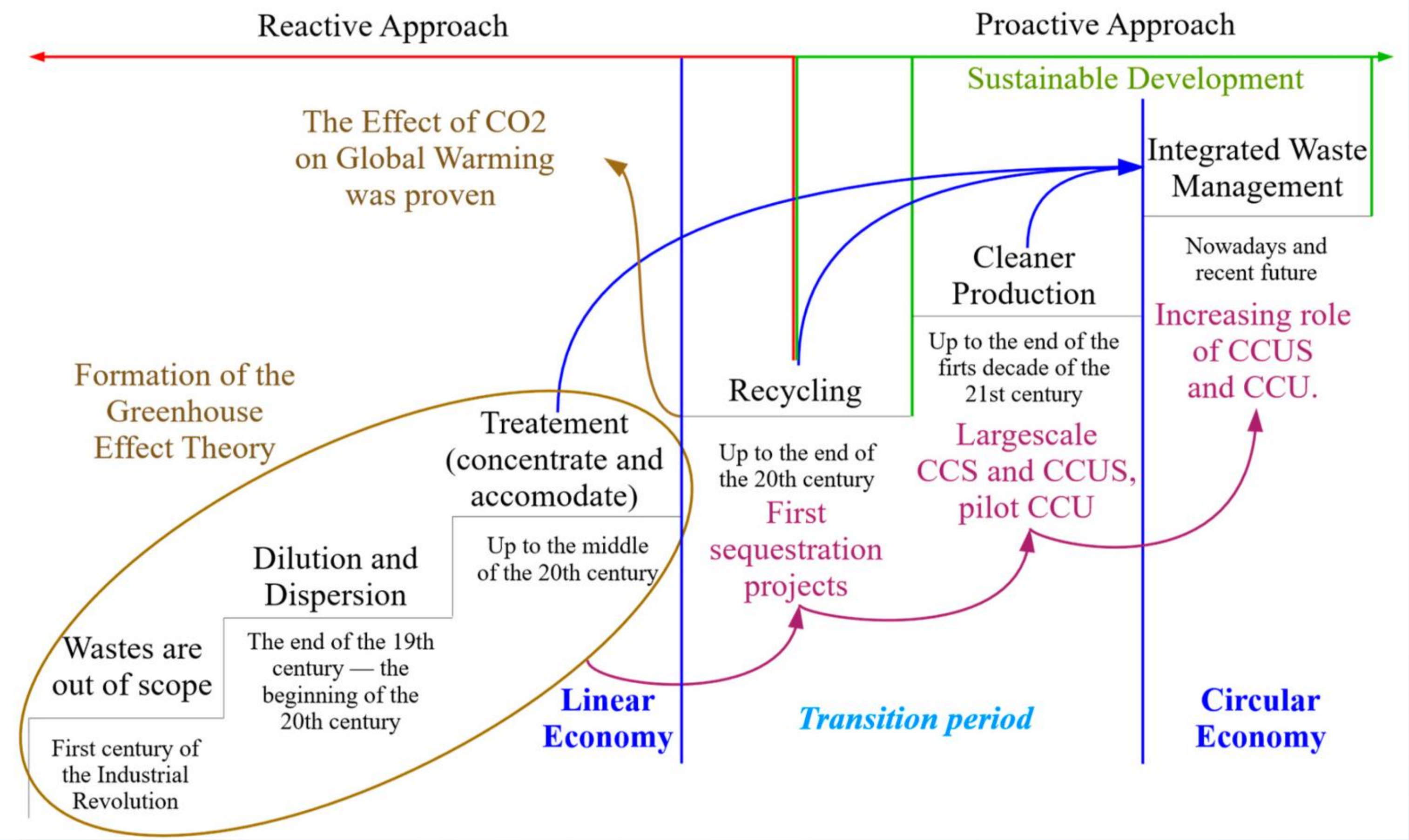
- On the other hand, studies associated with waste management are mostly focused on solid wastes, with the exception of the nuclear industry. The emergence of CCU technologies is to some extent a unique and innovative step, which adds a processing option to the traditional methods used to combat gaseous waste (capture and storage). Thus, without attention from the researchers to the comprehensive development of waste management (including gaseous wastes and air quality control) as part of the transition to a circular economy, a knowledge gap will appear in the coming years.

CO_2 in the transition to a circular economy

- Another unexplored issue is the changing role of CO_2 in the development of sequestration technologies. At the beginning of the century, companies were focused on carbon tax reduction rather than on using CO_2. However, currently there is a rapid development of cost-effective technologies for CO_2 processing. At the same time, CO_2 acts as a raw material for the production of not only new, but also existing products, which means that it can take a share of already formed markets.

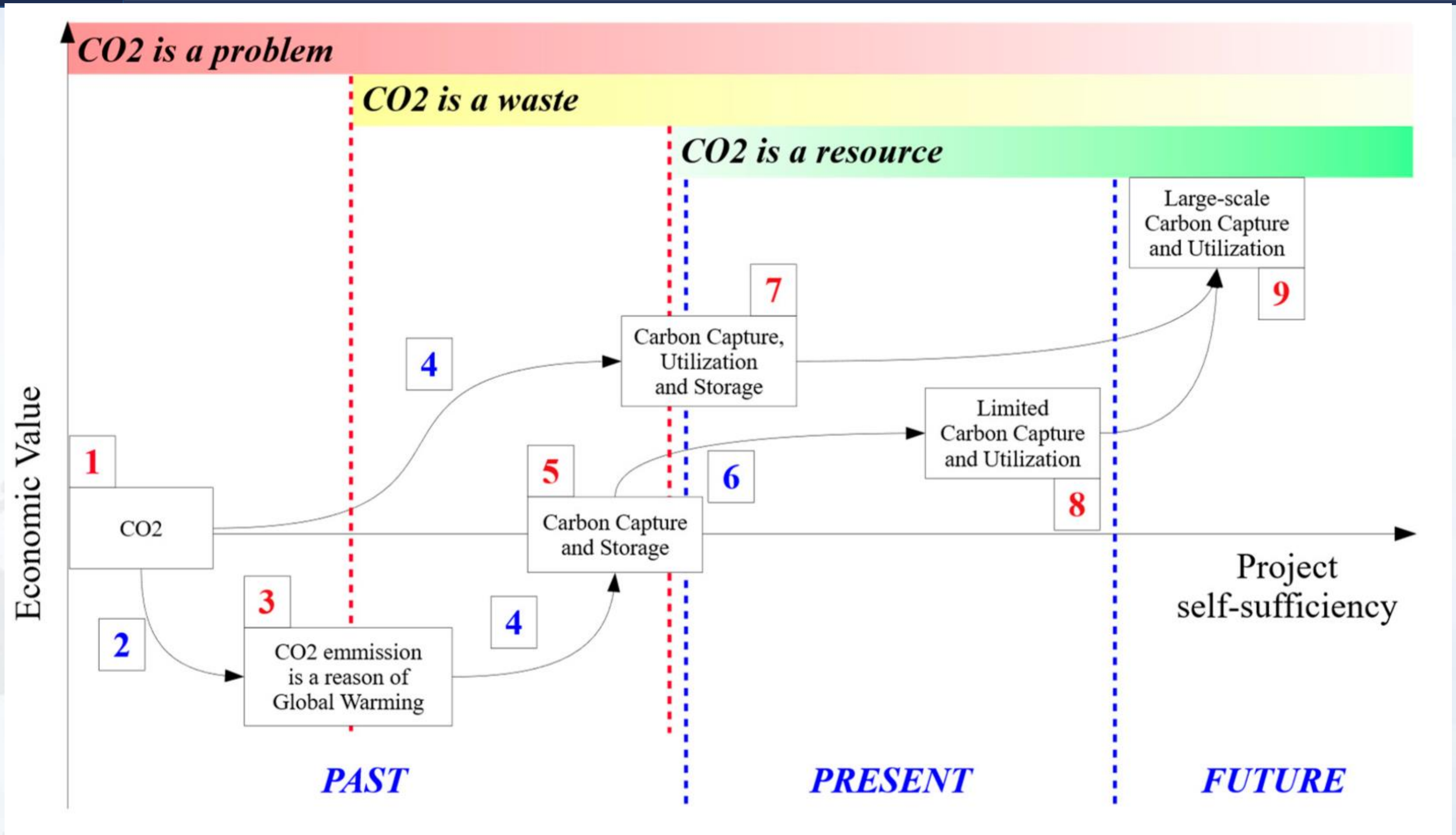
- The potential to enter existing and new markets is one of the key factors that determines the interest of industry and investors in CCUS and CCU technologies. Consequently, with the development of new, and improvement of existing, CO_2 utilization technologies, the rate of deployment of sequestration projects will increase, which is a positive trend in the context of sustainable development. This situation requires a revision of the attitude towards CO_2 and justification of its role in the world economy, not as a waste but as a useful resource that will lead to the formation of the so-called CO_2 economy

The changing role of CO2



The relationship between sequestration project development and the transition to a circular economy

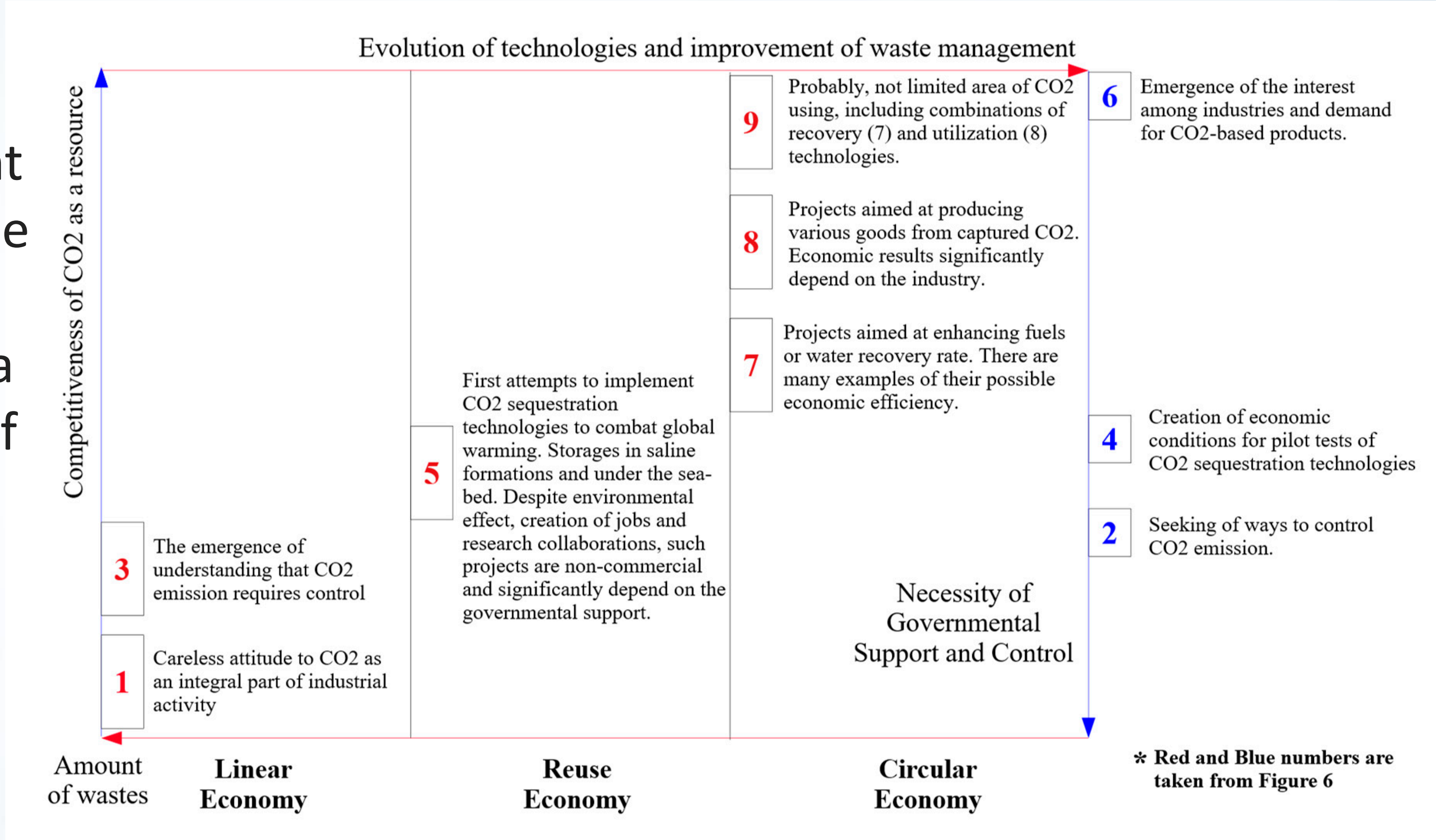
The changing role of CO2



Changing role of CO2 in the development of sequestration projects

The changing role of CO2

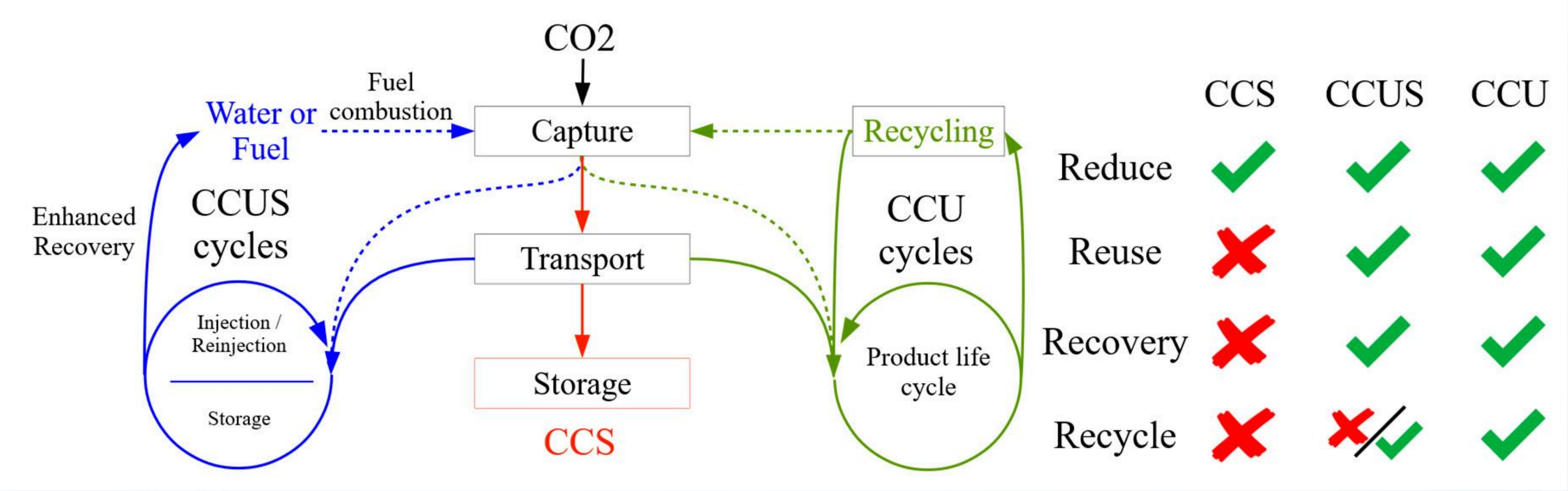
The circular economy and integrated waste management concepts assume at least three production stages that must be implemented when using a resource: reduce (limitation of technogenic CO_2 emission), reuse (using CO_2 in its initial form, instead of storing it), and recycle (processing CO_2-based products to create something new).



Conceptual vision of CO_2 sequestration options development

The changing role of CO2

As the figure shows, all the mentioned activities are possible only in the framework of CCU. However, it should be noted that CCUS, to a certain extent, also involves recycling, as enhanced natural resources can be processed using carbon capture technologies. Only CCS does not include any cyclic processes (in terms of CO_2 use), which allows one to attribute such projects to a linear economy.



Compliance of CO_2 sequestration options with the principles of a circular economy

Thanks for your attention!