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10 Insights from Industrial Ecology for the Circular Economy

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10 INSIGHTS FROM INDUSTRIAL ECOLOGY FOR THE CIRCULAR ECONOMY

International Society
for Industrial Ecology

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ABOUT THE PUBLISHER The International Society for Industrial Ecology (ISIE) (https://is4ie.org/) promotes the field of industrial ecology to address sustainability challenges and achieve a circular economy. The science of industrial ecology applies a systems perspective to explore how material and energy are used by society to find solutions to complex environmental problems. The ISIE facilitates communication among scientists, engineers, policymakers, managers and advocates who are interested in better integrating environmental concerns with economic activities. The mission of the ISIE is to promote the use of industrial ecology in research, education, policy, community development and industrial practices.

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FOREWORD

The optimisation of material use and minimisation of waste have been core topics in the field of industrial ecology since the early 1990s. Industrial ecology offers tools for modelling material stocks and flows (and, thereby, availability); helps identify opportunities to use waste material from one industry in another (industrial symbiosis); supports design for the environment; and provides methods for assessing impacts throughout the life cycle of products.

The methods and findings of industrial ecology are extremely relevant for designing a sustainable circular economy. Research into the circular economy has been ubiquitous among members of the International Society for Industrial Ecology (ISIE), albeit not fully coordinated. The present white paper is a landmark document because it represents the first overarching synthesis of industrial ecology knowledge in support of the circular economy.

I am sure this paper will be a very useful resource for science-policy exchanges. It can support outreach by ISIE members – many of whom are part of regional, national and international science-policy platforms – and inspire discussions between scientists, policymakers and industry. In addition, the paper can be a resource for teaching industrial ecology and circular economy, either to be used directly or to underpin the development of teaching materials.

The white paper is a prime example of successful collaboration within the ISIE to leverage academic knowledge to achieve social and policy impact. I would like to thank the authors wholeheartedly and congratulate them on the excellent outcome of their work.

On behalf of the ISIE, I wish everyone insightful reading!

Stefanie Hellweg
President of the International Society for Industrial Ecology
Professor of Ecological Systems Design, ETH Zurich

SUMMARY: INSIGHTS IN SHORT

1 Nature offers a model for industry
Industrial ecology draws an analogy between industrial activity and the natural cycles of materials and energy, which are a model for a circular economy. **08**

2 Societies metabolize like organisms
Industrial ecologists judge a society by its metabolism: the materials and energy it consumes, the activities this enables and the resulting waste and emissions. **12**

3 We cannot do without the environment
Whether linear or circular, the economy needs the natural environment, which provides essential resources such as food and materials and assimilates waste. **14**

4 Environmental impacts are inevitable
Because of its dependence on nature, a circular economy cannot avoid environmental impacts altogether, but it can target and reduce many of the impacts. **16**

5 A life cycle perspective avoids burden shifting
A life cycle perspective includes all impacts from raw material extraction to end-of-life waste to ensure that we don’t reduce one impact but increase another. **18**

6 Early systemic intervention prevents waste
Waste happens when material ends up in a place where it has no use, which can be prevented if we look ahead and design systems that are more efficient and last longer. **20**

7 Location shapes environmental impacts
The environmental impacts of human activity depend on where the activity takes place, which means the circular economy has to be different between locations. **22**

INTRODUCTION

This white paper presents 10 insights into the circular economy from the field of industrial ecology. Industrial ecology is a scientific field that takes a systems perspective to explore the society-wide use of materials and energy and address the related impacts on the natural environment. The circular economy is a framework for sustainable resource management that shapes government policy (McDowall et al. 2017), business model innovation (Lüdeke-Freund, Gold, and Bocken 2019) and public research agendas (Leipold et al. 2022).

The timeline (Figure 1) shows key publications for industrial ecology and the circular economy. The circular economy gained popularity in the 2010s through the efforts of, among others, the Ellen MacArthur Foundation. Industrial ecology was among its major sources of inspiration (EMF 2013). The beginning of industrial ecology is often traced back to the 1989 publication, "Strategies for Manufacturing", by Frosch and Gallopoulos, which discussed the environmental benefits of using industrial waste as a feedstock.

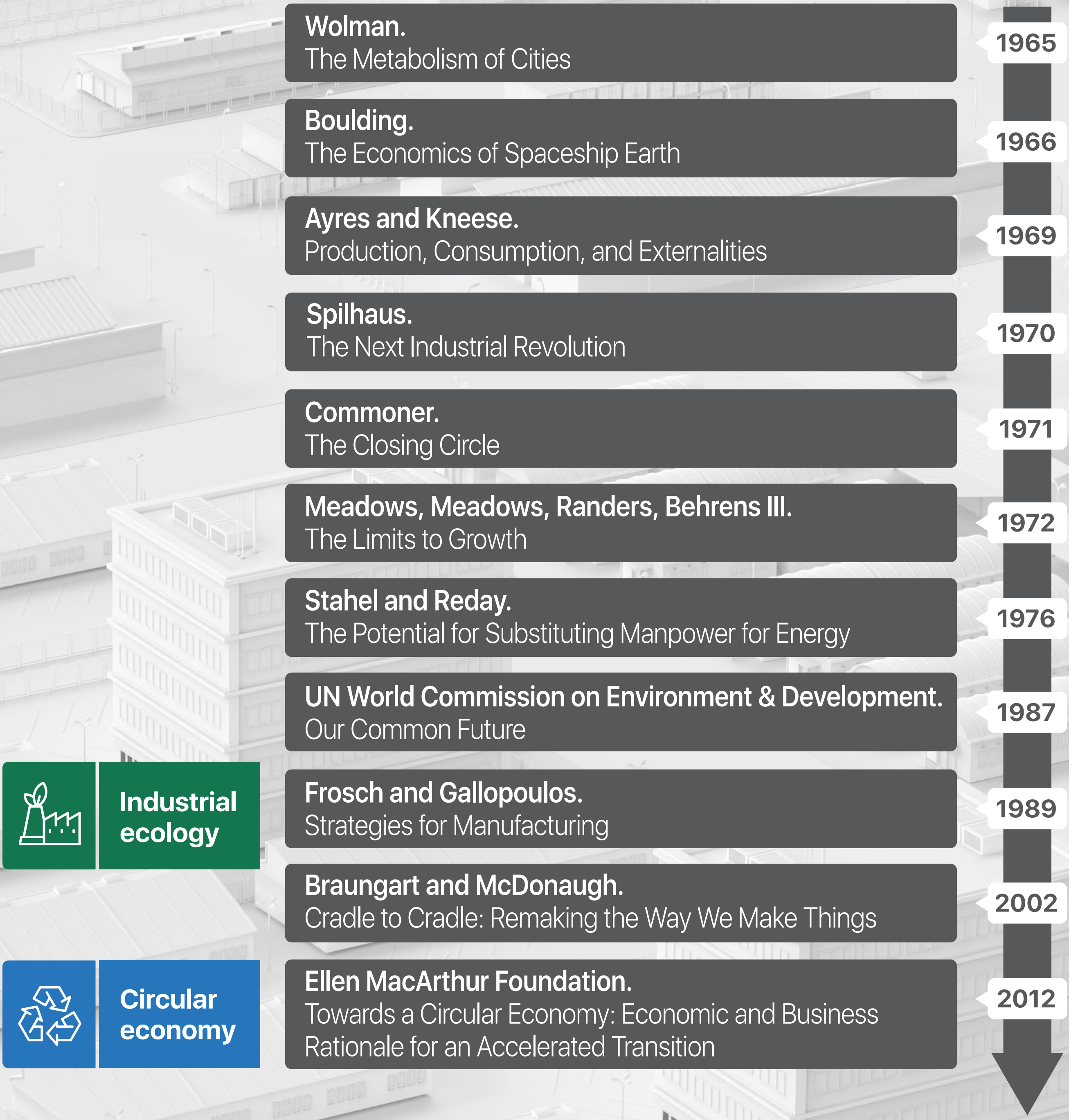
The circular economy discourse offers a new language for concepts with a longer history. Three decades ago, Robert Frosch (1992) already described an "industrial ecology system" that shares many traits with today's circular economy:

> **"By analogy with natural ecosystems, an industrial ecology system, in addition to minimising waste production in processes, would maximise the economical use of waste materials and of products at the ends of their lives as inputs to other processes and industries.**

Throughout its history, industrial ecologists have tracked the development of the circular economy concept, as well as the circularity of economies, including for China, Europe and globally (Haas et al. 2015; Yuan, Bi, and Moriguichi 2006).

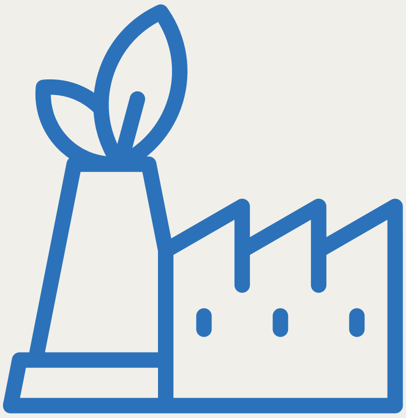
The circular economy has become a useful concept in sustainable resource management and an area of research that influences business and policy. The successful application of the circular economy benefits from extensive engagement with the body of scientific knowledge that brought it about, and which offers many relevant methods and findings. This white paper promotes such engagement by presenting 10 insights from the field of industrial ecology; each insight presents critical concepts, challenges, or opportunities for the circular economy.

The 10 insights aim to capture the full width of industrial ecology and invite readers to explore the full depth of each insight further through the cited literature. The development of the circular economy would benefit from engagement with each of these insights. A range of other fields and disciplines are also relevant to the circular economy and complement the focus of industrial ecology on technology, systems thinking and the environment. The successful development and implementation of the circular economy will require building on all these disciplines.



	Wolman. The Metabolism of Cities	1965
	Boulding. The Economics of Spaceship Earth	1966
	Ayres and Kneese. Production, Consumption, and Externalities	1969
	Spilhaus. The Next Industrial Revolution	1970
	Commoner. The Closing Circle	1971
	Meadows, Meadows, Randers, Behrens III. The Limits to Growth	1972
	Stahel and Reday. The Potential for Substituting Manpower for Energy	1976
	UN World Commission on Environment & Development. Our Common Future	1987
Industrial ecology	**Frosch and Gallopoulos.** Strategies for Manufacturing	1989
	Braungart and McDonaugh. Cradle to Cradle: Remaking the Way We Make Things	2002
Circular economy	**Ellen MacArthur Foundation.** Towards a Circular Economy: Economic and Business Rationale for an Accelerated Transition	2012

Figure 1 Seminal works in the history of sustainable resource management science.
Source: authors



Insight 1

NATURE OFFERS A MODEL FOR INDUSTRY

Industrial ecologists use nature as a metaphor for the development of several concepts and methods that also underpin the circular economy. Of these, the most fundamental are material and energy flow analyses. These methods are based on the concept of metabolism, which highlights that all organisms take in energy and/or matter, use energy for functioning and growth and release matter and energy that they cannot use. Similarly, all human activities, across spatial scales from factories to countries, consume energy and matter to conduct useful work and create products and generate waste (Ayres 1989; Ehrenfeld 2004).

In nature, however, we observe very little waste: decomposition and recycling of matter take place over varying timescales with some materials made available in relatively short times (e.g., plant matter), and others (e.g., fossils) essentially stored and unavailable for use for millennia. Nature also shows that the potential to cycle materials locally may be limited by the type of the materials and the presence of appropriate species that are able to break down and transform these materials into useful forms for use by other species — akin to the constraints of reusing waste in industrial societies.

Inspired by natural ecosystems, the circular economy aims to close material and energy loops, which requires an understanding of the spatial, temporal and functional complexities of material and energy flows, as well as their impacts on nature. Material and energy flow analyses are fundamental to making informed process design decisions and assessing systemic spatial and temporal limitations to circularity within global supply chains. A circular economy should not only consider what products and materials can be cycled but also where, when, how, how much, of what type and quality and by whom.

INDUSTRIAL SYMBIOSIS

Industrial symbiosis is a core concept within industrial ecology that involves the substitution of conventional resources (materials, energy, water) in an established activity for by-products from one or more other activities, which are often industrial and located nearby (Chertow 2000a). The right-hand side of Figure 2 provides an example of industrial symbiosis, which mimics the food web on the left-hand side (Hardy and Graedel 2002). Sokka et al. (2011) analysed the environmental benefits of industrial symbiosis around a pulp and paper mill. They identified exchanges of chemicals, fuels, solid wastes and steam. These exchanges led to 5–20% reductions in various environmental impacts.

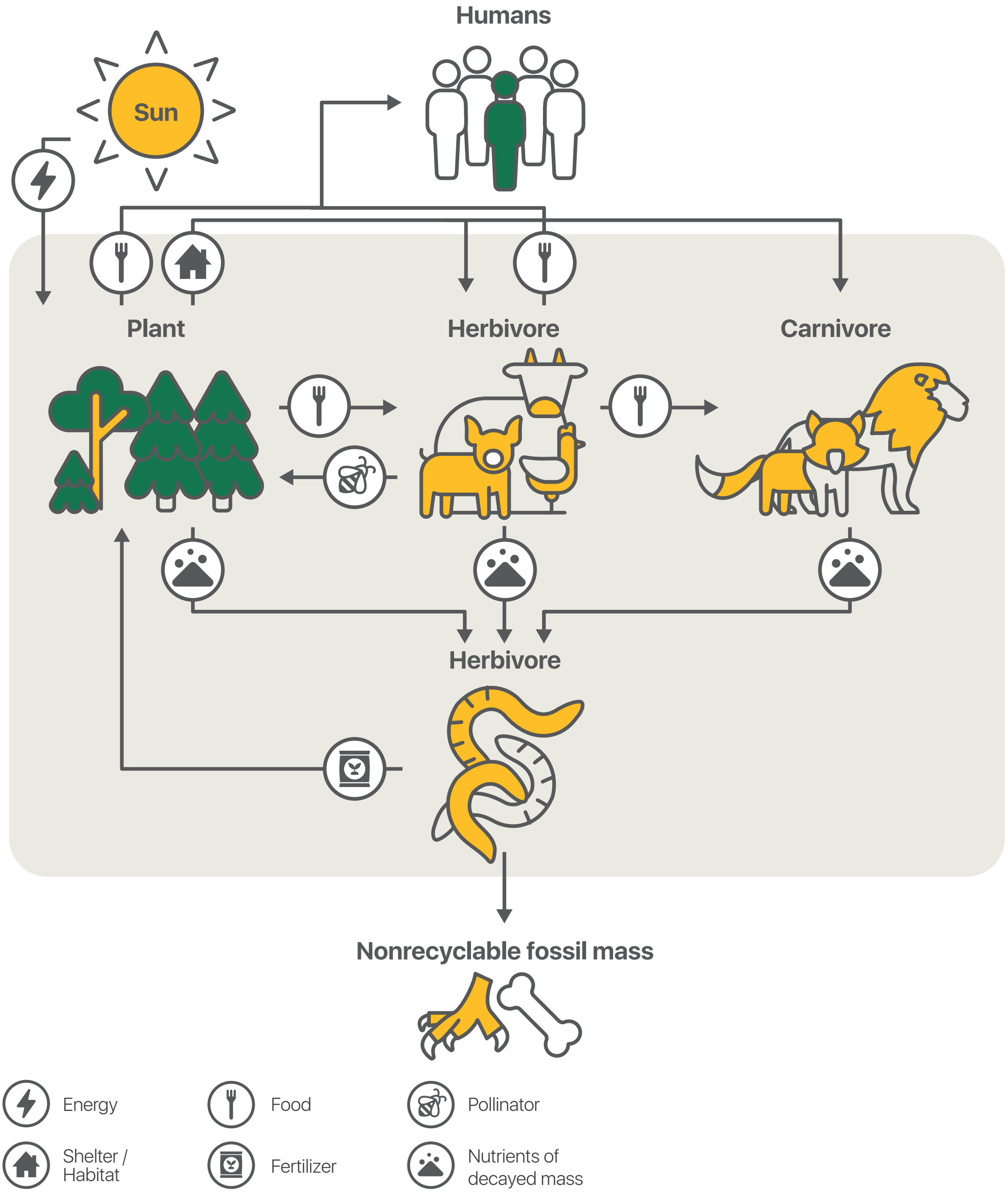


Figure 2 The flows of material, energy and water in ecosystems (previous page) are mimicked in an industrial symbiosis between firms that exchange waste as a resource (current page).
Source: Lao et al. (2020) and Kalundborg Symbiosis

Insight 2

SOCIETIES METABOLISE LIKE ORGANISMS

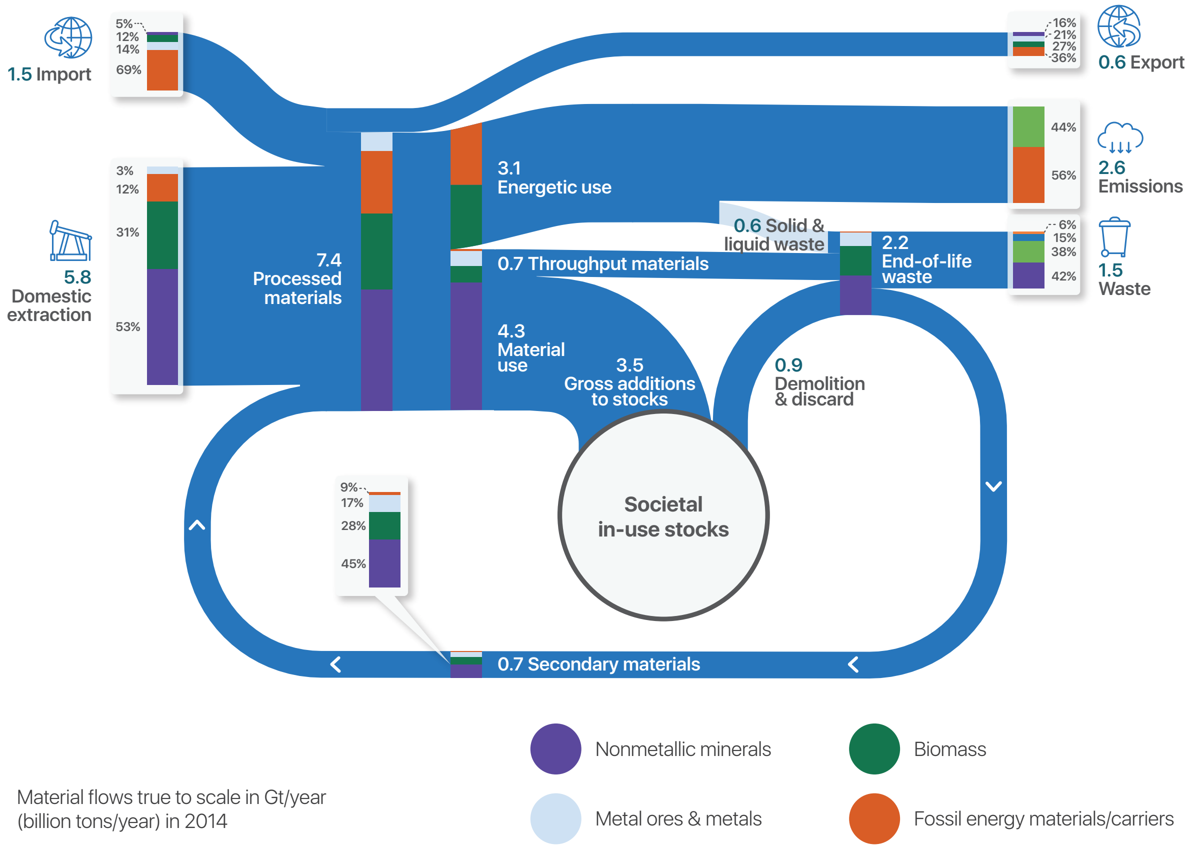
Socio-economic metabolism (also referred to as industrial metabolism, society's metabolism, or anthropogenic metabolism) is at the heart of industrial ecology and the circular economy. It applies the biological concept of metabolism to describe the ways in which human systems process resources. Examples of socio-economic metabolism include the conversion of raw resources through chemical and physical means into useful energy such as refined fossil fuels; the use of construction materials to grow and maintain the built environment; and the accumulation of materials for goods and products (society's capital stocks). Ultimately, the materials in societies become wastes and emissions. The transformations of energy and material sources into useful forms are driven by labour, capital and technology and provide society with goods and services, such as homes, infrastructure, transportation and communication – with the ultimate objective of increasing the wellbeing of people (Ayres 1989; Baccini and Brunner 2012; Fischer-Kowalski 1998).

Resources can be tracked and accounted for through societal metabolic processes to quantify the useful energy and materials that they provide, as well as the losses, wastes and impacts on the surrounding environment. Materials and energy adhere to laws of conservation and are subject to physical limitations of efficiency, dissipative losses and entropy (Cullen 2017). Industrial ecologists apply the notion of socio-economic metabolism at multiple – and often interlocking – scales, from the transformations and utilisation of materials and energy on the level of the global economy, through to those of individual countries and cities, and down to individual households and industrial plants.

Industrial ecology offers material flow analysis to study socio-economic metabolism, including material, energy and substance flow and stock accounting. These methods are used to describe normatively society's consumption of materials and energy on multiple scales and for different purposes, and increasingly to describe different potential futures to inform sustainable resource use (Schandl, Müller, and Moriguchi 2015).

SOCIETAL METABOLISM AS AN INDICATOR OF CIRCULARITY

The metabolism of a region gives an indication of the circularity of energy and material use. Mayer et al. (2019) conducted a material flow analysis of material and energy consumption in the European Union (Figure 3) and derived circularity indicators. The analysis combined data on resource extraction, consumption and waste according to the mass balance principle (mass cannot disappear: what goes in, goes out, or stays in stock). They found that only 10% of inputs into the economy are secondary materials and only 15% of waste was cycled back into the economy.



Material flows true to scale in Gt/year
(billion tons/year) in 2014

Figure 3 A Sankey diagram of socio-economic metabolism in the European Union using material flow analysis methodology. The flow width represents the quantity of material. The bar charts indicate the flow composition.
Source: Mayer et al. (2019)

Insight 3

WE CANNOT DO WITHOUT THE ENVIRONMENT

All economies, whether linear or circular, are dependent upon the capacity of ecosystems to act as a source of materials and energy, and as a sink for emissions and wastes. While historic agrarian societies were limited in their growth and development due to the natural geographical availability of energy and resources, modern (predominantly industrial) societies are increasingly exceeding the natural ability of ecosystems to absorb emissions and waste (Krausmann et al. 2008).

Industrial ecology has been defined as "the means by which humanity can deliberately and rationally approach a desirable carrying capacity" (Graedel and Allenby 1995). The capacity of ecosystems to supply resources and absorb waste is an "environmental limit" that defines the safe space for resource consumption. At the global scale, these environmental limits are represented by the planetary boundaries concept (Rockström et al. 2009). Surpassing these limits threatens to trigger the breakdown of ecosystem integrity and, hence, the socio-economic systems dependent on them.

Strategies for circular use of resources can reduce pressures on the environment, but societies will always remain dependent on nature. A circular economy can approximate the cycles of nature, but not achieve a perfectly closed loop. Some virgin material is always required to keep a circular economy going, and some waste will always need to be disposed of (Kral, Kellner, and Brunner 2013). Given the limitations of the environment, one of the major questions is how to allocate scarce resources among people globally (Sabag Muñoz et al. 2017).

The embeddedness of the economy in nature complicates economic growth. Many countries pursue a decoupling of the economy from the environment: they aim to achieve economic growth without growth in the associated environmental impacts. However, industrial ecology research shows that most countries only achieve relative decoupling – resource use and greenhouse gas emissions are still growing, just not as fast as the economy (Schandl

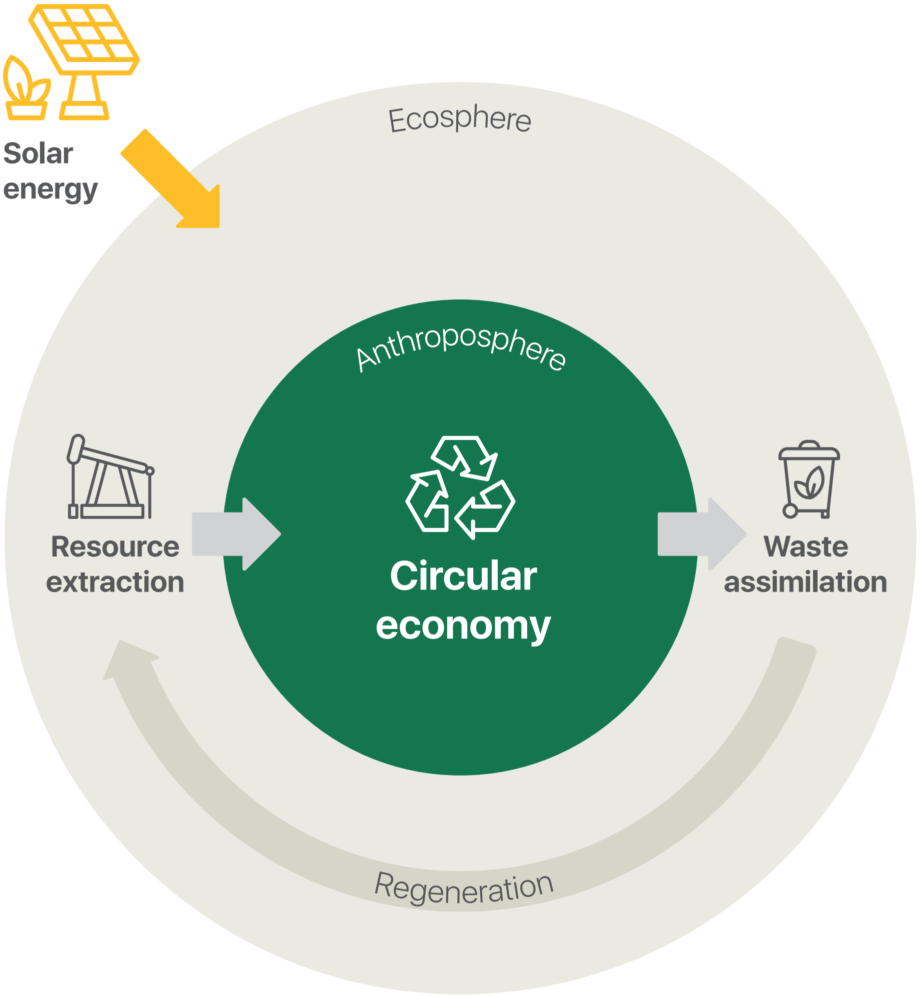


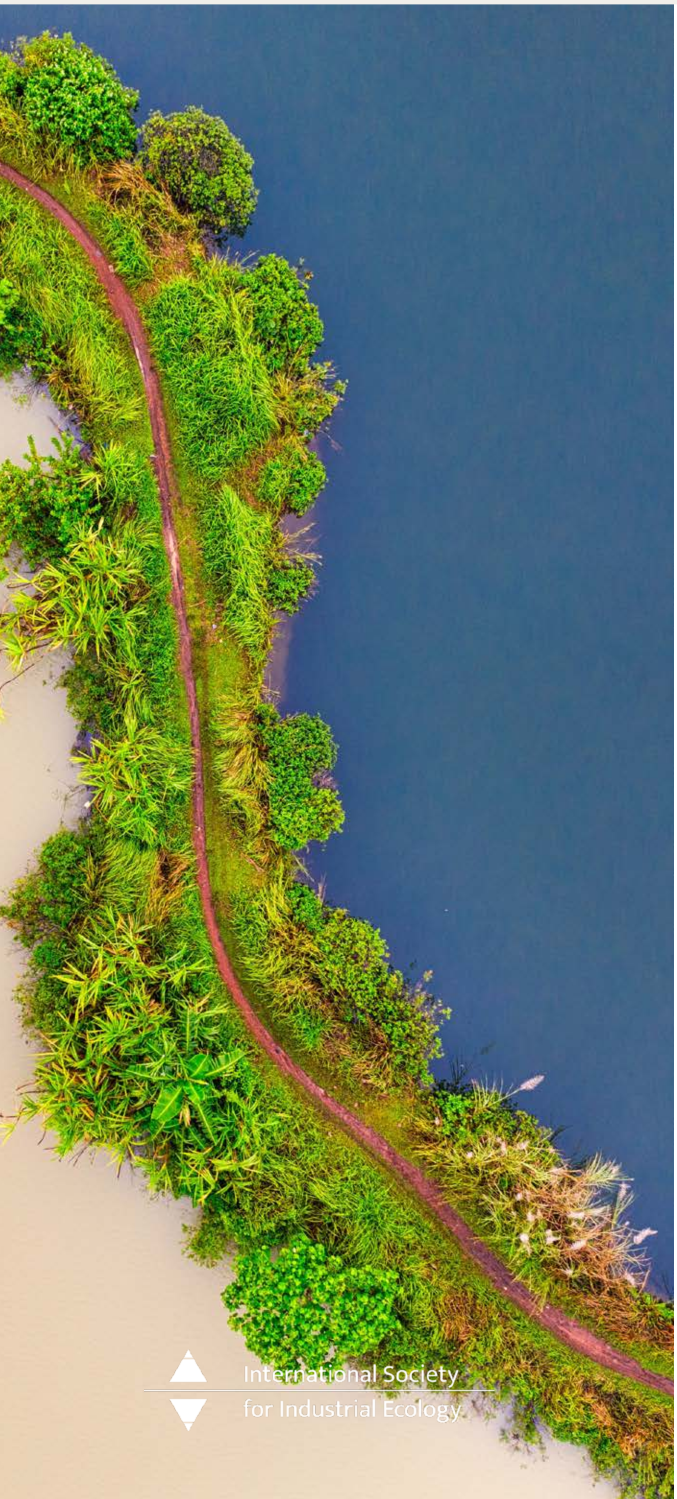
Figure 4 Societies take resources from the environment and return waste. Any economy is critically dependent on exchange with the environment.
Source: authors

CLOSING THE CYCLE OF TOXIC HEAVY METALS

Three decades ago, a presentation at the Industrial Ecology colloquium at the National Academy of Sciences described the fundamentals of the circular economy (Ayres 1992). It laid out the imperative and challenge of closing the material cycle, with a focus on toxic heavy metals. The planet is a source of very useful metals for many applications, such as batteries and healthcare technology, but they are toxic to people and ecosystems when discarded into the environment. The metals may safely accumulate in the anthroposphere – in products, buildings and permanent waste storage – but should be cycled to prevent leakage into the environment. We should also avoid certain uses of these metals, such as leaded fuel, which inevitably and irreversibly disperses lead into the environment.

Insight 4

ENVIRONMENTAL IMPACTS ARE INEVITABLE



Since industrial systems are embedded in nature, the use of materials and energy by society always creates some environmental impacts. Circular material flows are not a recipe for zero impacts, but strategies to pursue more advantageous trade-offs between environmental and social/economic benefits. A fully circular system is impossible because it violates the laws of thermodynamics (Cullen 2017). For example, it would require an infinite amount of energy to recycle waste totally because it involves undoing the spreading, mixing and dissipation of all waste materials.

Circular economy strategies can result in products with lower impacts. However, the impacts are strongly dependent on how, where, when and to what extent a strategy is implemented. For example, paper recycling can be counterproductive when it is dependent on fossil fuels (van Ewijk, Stegemann, and Ekins 2021) and some chemicals are too hazardous to be recycled (Singh et al. 2021). As such, indicators for the monitoring of the circular economy should not only capture cycles, such as the reuse or recycling rate, but also account for the associated environmental impacts (Helander et al. 2019).

When comparing options, it is often necessary to identify trade-offs between environmental impacts, such as between emissions of greenhouse gases and toxins. For instance, electric vehicles tend to contribute less to climate change than internal combustion vehicles, but the production and waste management of batteries can lead to the release of toxic chemicals (Hawkins et al. 2013). Industrial ecology offers methods to assess these impacts to avoid the inadvertent worsening of some problems when trying to solve others (Melin et al. 2021). After all, circular flows should not be an end in itself, but a means to reduce environmental impacts where appropriate.

CIRCULAR ECONOMY REBOUND

Circular strategies, such as reuse, promise to reduce environmental impacts. However, when such strategies reduce the costs of products, consumption may increase, partially offsetting the environmental benefits (Zink and Geyer 2017). For example, used products cost less so we buy more of them. Moreover, used products do not always displace new products. Instead, we may purchase both (Figure 5). The “circular economy rebound” may be lessened by prioritising actions based on a system understanding of indirect effects in production and consumption. The circular economy rebound is a manifestation of the more widely applicable “rebound effect” first observed by the economist Jevons and widely studied in industrial ecology (Hertwich 2005).

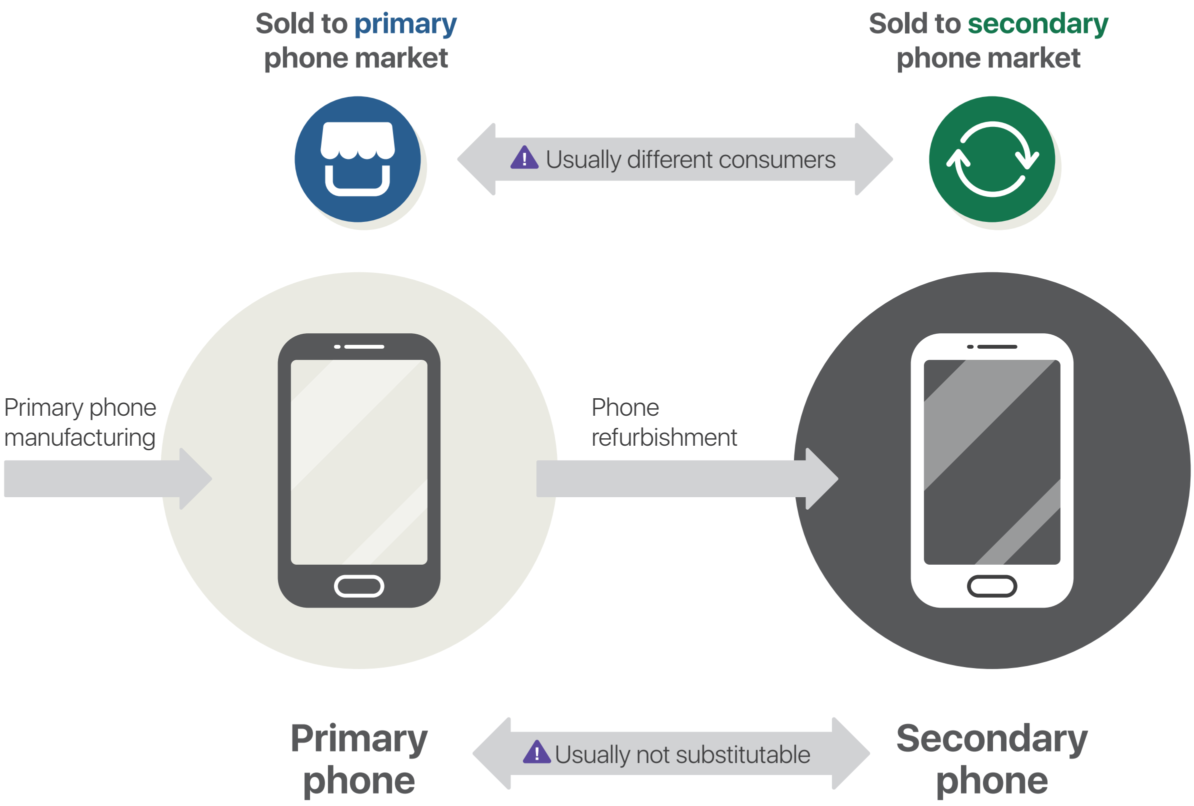
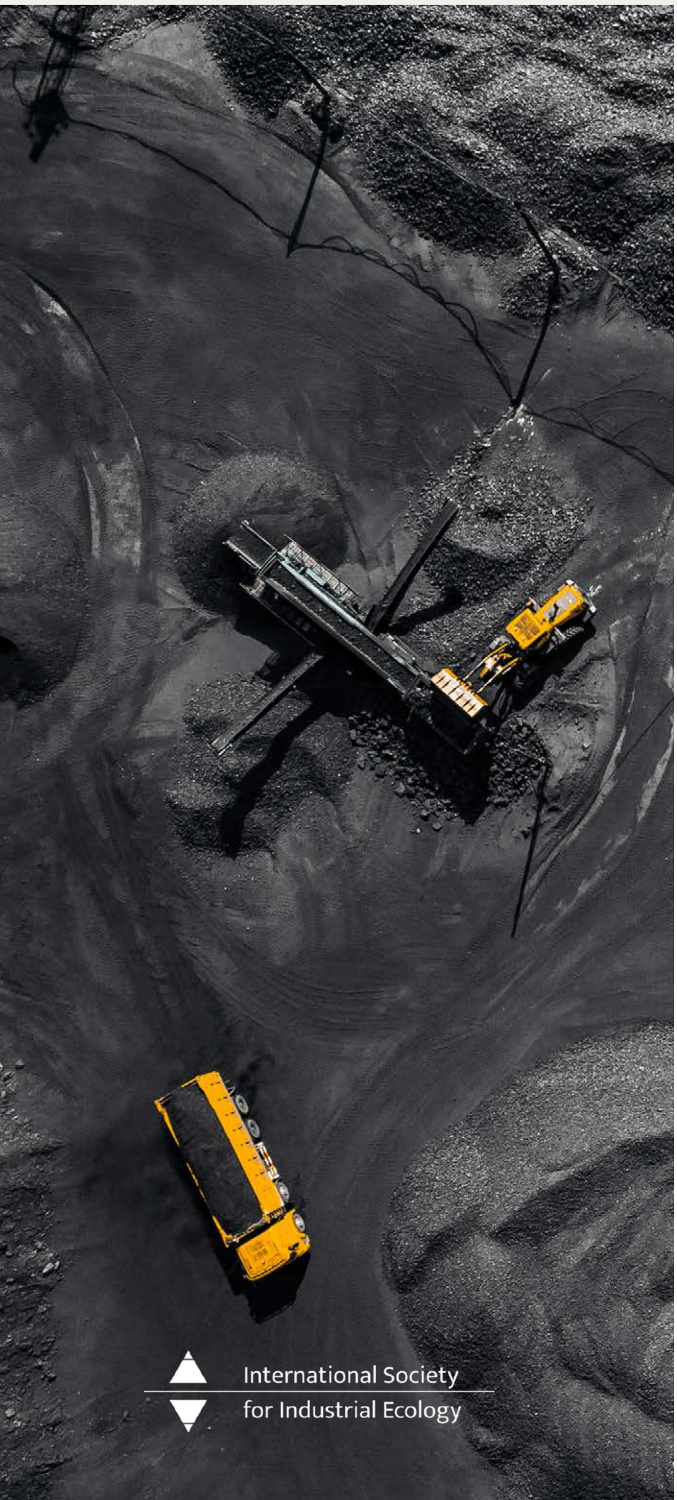


Figure 5 Refurbishing phones leads to increased total phone consumption, since primary and secondary phones are imperfectly substitutable and it leads to increased secondary phone ownership. This represents an increase in resource use and environmental impacts, despite phone refurbishing having a lower environmental impact than primary phone manufacturing.
Source: authors

Insight 5

A LIFE CYCLE PERSPECTIVE AVOIDS BURDEN SHIFTING



One of the major challenges when reducing environmental impacts is to avoid burden shifting between types of environmental impacts and across life cycle stages. For example, a more energy-efficient building may require building materials that are energy-intensive to manufacture, partly offsetting the energy savings during the use of the building. Even if the manufacturing were energy efficient too, it may require harmful chemicals. The transfer of impacts between categories or life cycle stages is called burden shifting.

A life cycle perspective is critical to the development of a circular economy because it avoids burden shifting by considering all life cycle stages and various types of environmental impacts when assessing a product, service or system. Environmental life cycle assessment considers ecological burdens that occur 'upfront'; for instance, from resource extraction and product manufacturing; those that occur during the distribution and use of a product; and those occurring at end-of-life, when a product enters waste management systems and may be partially recovered for recycling or reuse.

Life cycle assessment is often applied to compare products that fulfil the same function – such as different types of transport to move people or goods, or residential buildings to house people. It is also applicable on a larger scale; for example, in comparing circular economy strategies (Cooper et al. 2020). Social and economic impacts can also be incorporated through life cycle sustainability assessment, considering factors such as labour conditions, exposure to health hazards, or human rights issues along the supply chain of a product (UNEP 2020). Industrial ecologists have made major contributions to the standardisation, guidance and application of life cycle assessment (Guinee et al. 2001).

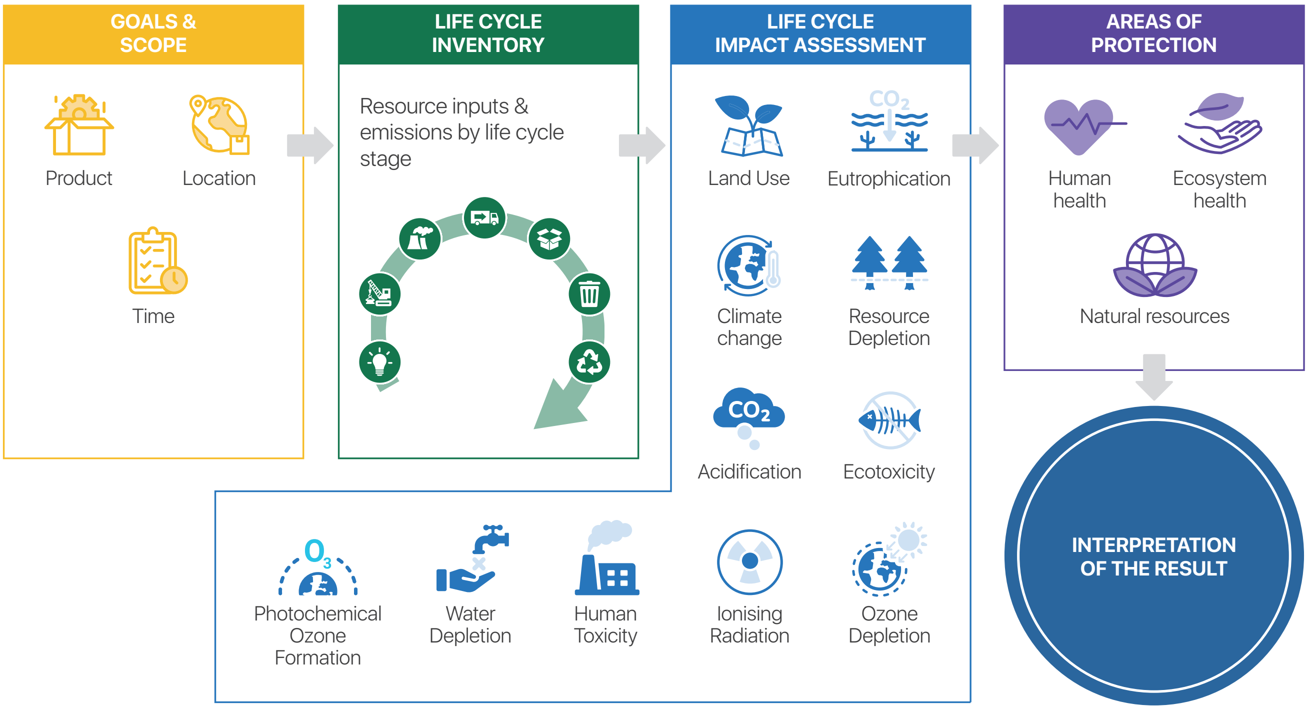


Figure 6 Life cycle assessment identifies the inputs and outputs of materials and energy across all life cycle stages and the associated environmental impacts. It consists of four stages that have been formalised in the ISO standard (ISO 2006).
Source: authors

MANAGING POLY- AND PERFLUOROALKYL SUBSTANCES (PFAS) POLLUTION

Many carpets contain poly- and perfluoroalkyl substances (PFAS), which are persistent toxins that cause harm upon exposure when released into the air or leaching out of material that is in use or at end-of-life. A circular economy should avoid such chemicals, but how? A material flow analysis by Chen et al. (2020) shows that eliminating emissions of PFAS in the production stage has a limited effect on these emissions during the use and end-of-life life cycle stages. The modelling of PFAS stocks and flows shows that a systemic approach is required to reduce PFAS emissions from both new products and those that are already in use.

Insight 6

EARLY SYSTEMIC INTERVENTION PREVENTS WASTE

Industrial ecology research shows that early intervention from a life cycle perspective tends to yield greater environmental benefits than end-of-pipe pollution control and waste management. A good example is food waste, where prevention leads to larger reductions of greenhouse gas emissions than recovery of the materials and energy through incineration and anaerobic digestion (de Sadeleer, Brattebø, and Callewaert 2020). Further assessments have shown the contributions of food waste prevention to the protection of the climate, biodiversity and other impacts (Beretta and Hellweg 2019).

Almost any strategy for impact reduction requires a systemic approach. For instance, to increase metal recycling, the activities across the entire life cycle must be considered. The main challenges that must be met include more extensive collection of end-of-life products, design improvements to enable disassembly and recycling and further advancement in recycling technology (see Figure 7) (Reck and Graedel 2012). Since these activities are complementary, some forms of coordination are essential, such as the standardisation of assembly and disassembly techniques.

Studies in industrial ecology show that better product design and new business models are critical to waste prevention (Bocken et al. 2016). In a circular economy, products might be designed to last longer, serve a second purpose, or allow repair and upgrading. Such products do not fit with a business model that relies on selling more, faster. Instead, businesses may focus on selling durable quality at a premium, sell products through service agreements such as a rental contract and develop repair as a commercial activity. Both product design and the business model should accommodate the collection and treatment of the product when it is ultimately discarded.

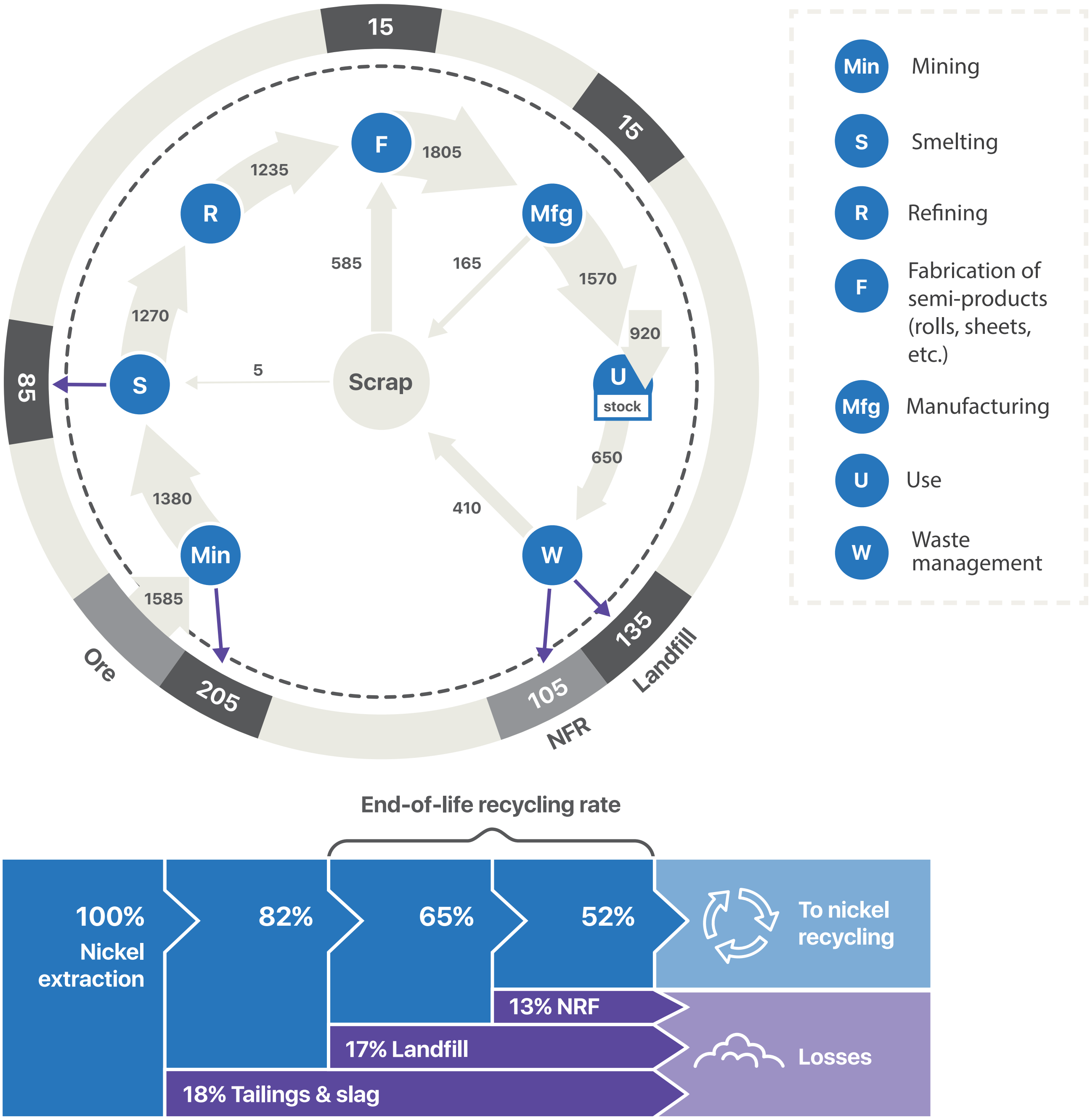


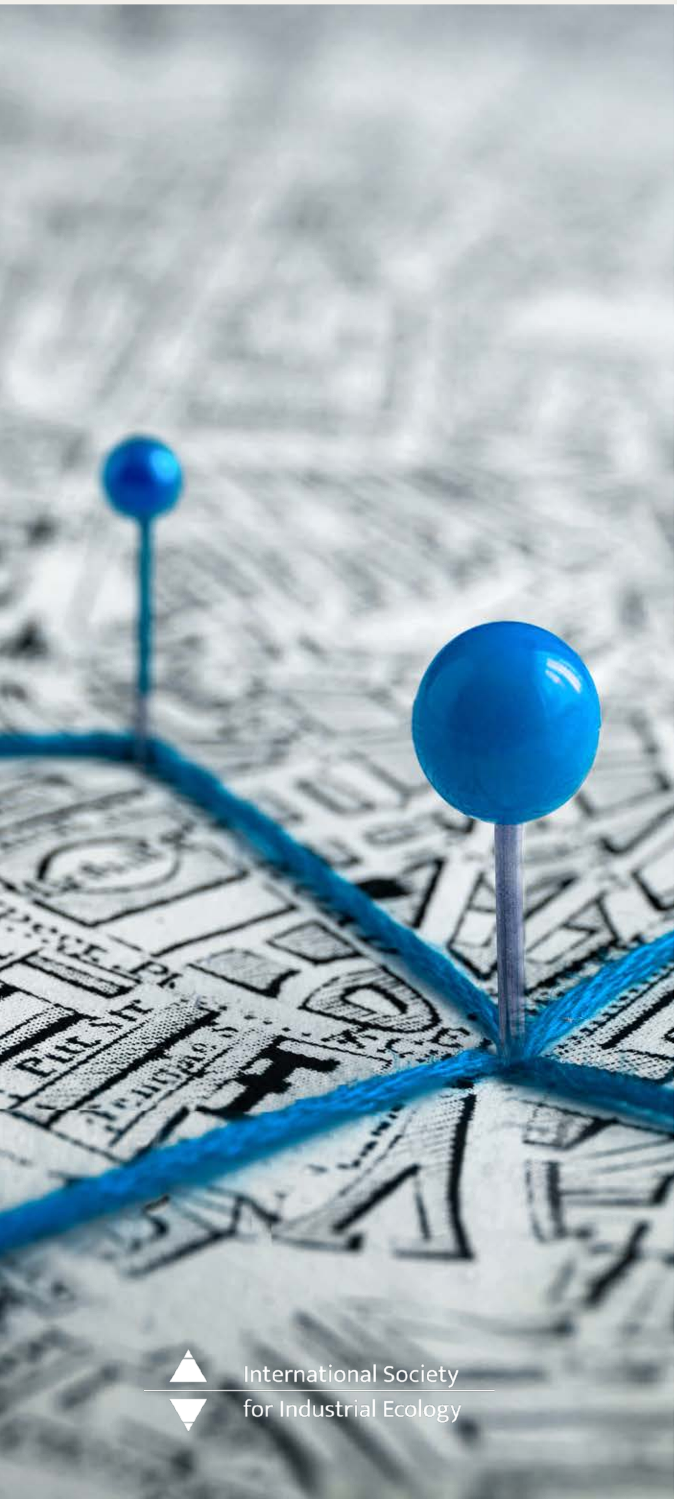
Figure 7 The global cycle of nickel and the major losses of nickel throughout the life cycle. Greater nickel recycling requires intervention across the life cycle.
Source: Reck and Graedel (2012)

MAKING PRODUCERS LOOK AHEAD

Early systemic intervention needs stakeholders across the life cycle willing to act. With Extended Producer Responsibility (EPR), governments can make producers responsible for the end-of-life stage of their products, either by making them take back their old products or having them pay the waste management costs. Ideally, green design choices such as recyclability and durability are more advantageous to producers when faced with EPR. The potential and pitfalls of EPR have been widely studied in industrial ecology, supporting the implementation and evaluation of such schemes around the world, such as for electronics and packaging (Atasu 2018; Lifset, Atasu, and Tojo 2013).

Insight 7

LOCATION SHAPES ENVIRONMENTAL IMPACTS



A universal recipe for circularity cannot exist because the impacts of material, product and industrial systems depend on where the relevant activities happen. Life cycle assessment studies have shown substantial differences between the environmental impacts based on the regional conditions; for example, in the case of electricity generation (Mutel, Pfister, and Hellweg 2012) and agricultural production (Raschio et al. 2018). Understanding these regional variations is important for decision-making: what works best in one place, may not be the best option in another.

Regionalised life cycle assessments can identify burden shifting between countries, which occurs when goods are produced in one country but consumed in another. The burden is often shifted from high-income countries, which purchase many goods, to low-income countries that manufacture the goods (Wood et al. 2020). Spatial burden shifting is often shown through (multi-regional) input-output analysis – a key tool in industrial ecology – which estimates environmental impacts of production or consumption, based on economic accounts of production, consumption and trade between countries, and national resource and environmental statistics.

Spatial scale also matters for infrastructure because decision makers, including urban planners, need to know where materials accumulate in infrastructure and how this affects the need for energy and materials. For instance, buildings in the circular economy need to match the local availability of resources for heating, cooling and maintenance. Finally, a spatial understanding is key for matching the generators and potential users of secondary resources (Li et al. 2020). Spatial analysis can be used to identify the availability and location of secondary resources; the distances between generators and users of such materials; and the planning of processing facilities and logistics.

THE WATER FOOTPRINT OF COUNTRIES

The water footprint indicates the amount of ground and surface water used to deliver a product or service, such as the water required to irrigate crops, supply drinking water or produce a paper cup. Since products are traded globally, the required water is indirectly traded as well. Much of the water that is consumed indirectly has virtually travelled across borders – almost half of the water used to meet consumption in the European Union is supplied by water from outside the EU, where the products were made or harvested (Figure 8).

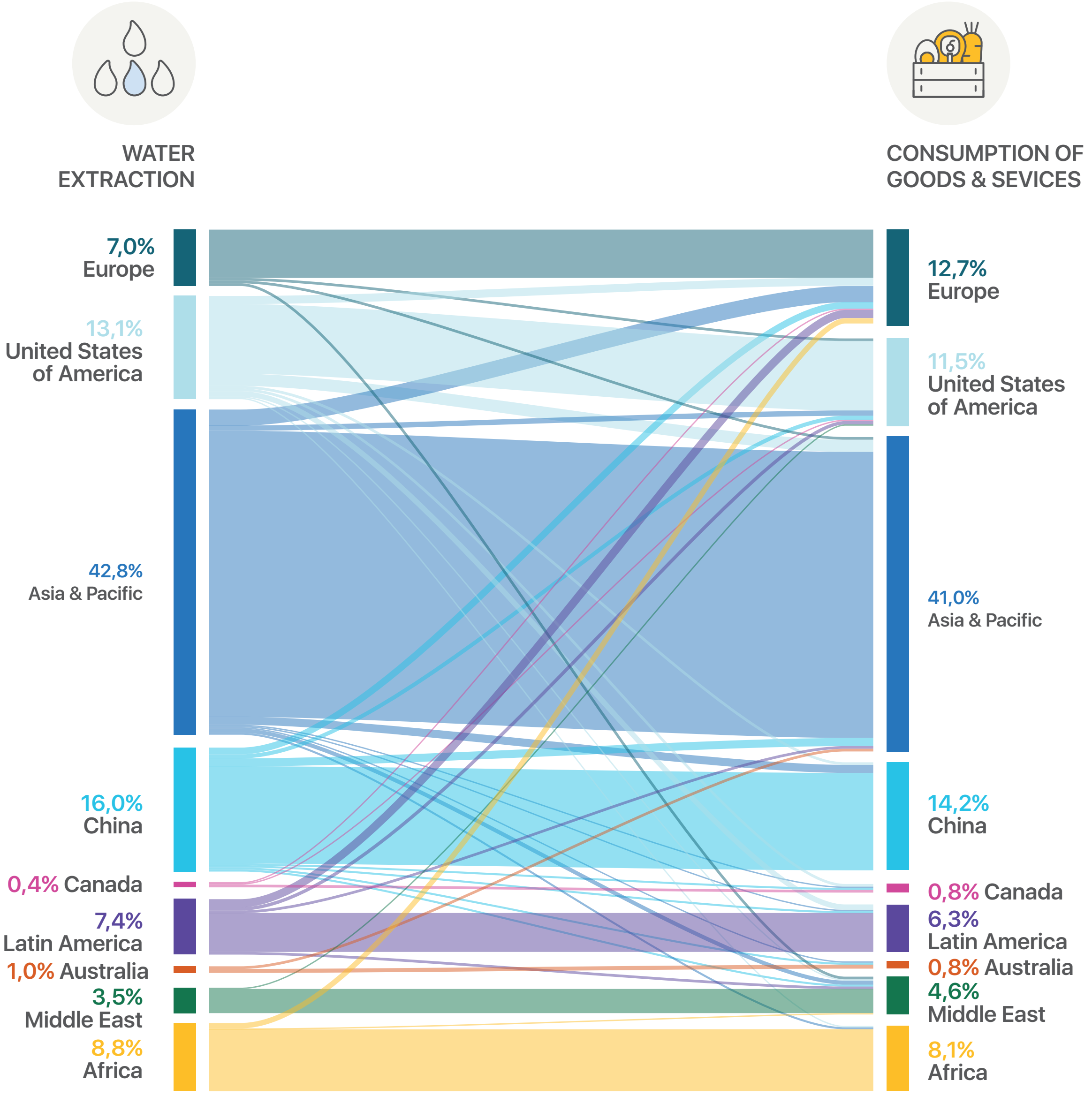


Figure 8 Origins of water extracted to meet the consumption of goods and services in world regions, as a percentage of total extraction and use. Regions with a much larger percentage on the right-hand side than the left-hand side are strongly reliant on water extraction abroad to meet their needs.
Source: Tukker et al. (2014)

Insight 8

MATERIAL USE DEPENDS ON INFRASTRUCTURE

The metabolism of society depends on the nature of its material infrastructure that support socio-economic activity: buildings for shelter and workplaces; roads for mobility, cables for communication; and pipes for water supply and sanitation. As global prosperity rises, large amounts of depletable minerals and fossil fuels have been extracted and transformed to build up, renew, renovate and operate infrastructure, which, in turn, drives the anthropogenic cycles of materials and energy (Krausmann et al. 2017). The systemic drives of material use for infrastructure are shown in Figure 9.

Due to its long lifespan, infrastructure usually has a slow turnover (years to centuries); therefore, changes in the lifetime, material composition and in-use performance of infrastructure can impact the metabolic pattern of human society for decades – potentially leading to long-term path dependency on unsustainable material and energy consumption patterns (Müller et al. 2013). For example, road infrastructure requires maintenance decades into the future and can lock societies into the use of cars for as long as the infrastructure can be feasibly maintained (Unruh 2000).

Decision-makers aiming for a circular economy must understand how infrastructure can lock future generations into high material and energy demands (Pauliuk and Müller 2014). Studies in industrial ecology show how society extracts, transforms and accumulates materials (‘material stocks’), which can support the circular economy, but also disaster relief: Tanikawa, Managi, and Lwin (2014) created a database of the type, quantity and location of materials in buildings and infrastructure in Japan to estimate material losses and waste disposal needs after the 2011 earthquake and tsunami.

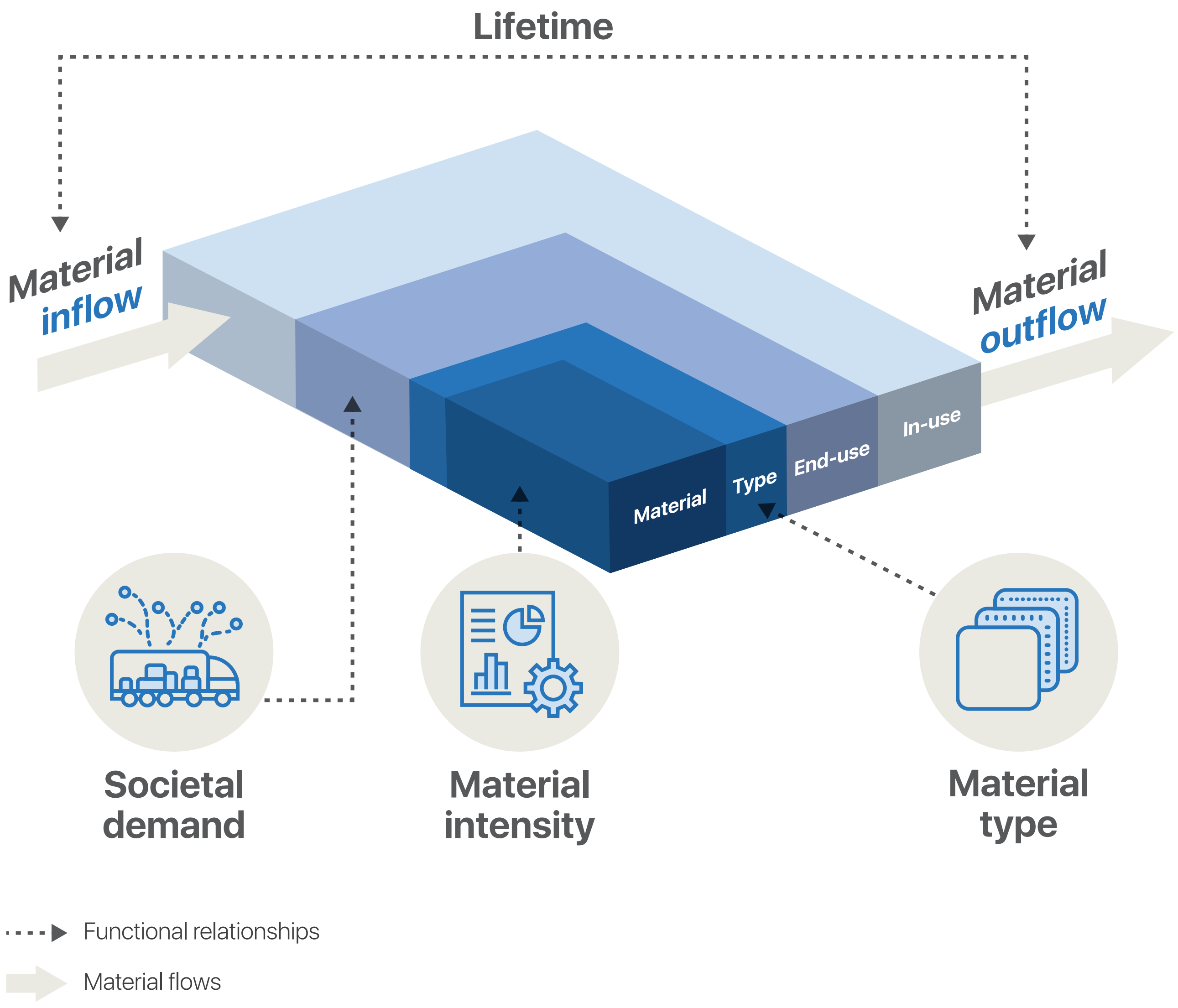


Figure 9 Factors that influence the amounts of materials stored in infrastructure. Solid arrows represent material flows; dashed arrows show functional relationships.
Source: authors

INFRASTRUCTURE CREATES LOCK-INS

It takes materials and energy to build a house, but also to use and maintain it, and to replace it at the end of life. In turn, demolished buildings may provide materials for new housing. A study by Müller (2006) demonstrates how stock dynamics can lock society into patterns of material and energy use. The research found that the use of building materials is shaped by population growth, the number of people in a household, the lifetimes of buildings and the amount of materials required per unit of floorspace (which depends on the architecture and building technology). Understanding these patterns is essential for planning future material use and reducing environmental impacts.

Insight 9

TECHNOLOGY IS NOT A PANACEA

Industrial ecology and the circular economy emphasise the role of technology in reducing environmental impacts from production and consumption. However, industrial ecology shows that environmental impact is also mediated by at least two other factors: population and affluence. The relationship between impacts, population, affluence and technology is famously described in the IPAT equation (Chertow 2000b). The IPAT equation, illustrated in Figure 10, shows that environmental impacts may grow with population, affluence and technology unless such growth is offset by decreases in one or more of these three factors.

The technology factor summarises how we use energy and materials, which is the combined result of the choice of technology (e.g., cars, buildings) and how we use technology (e.g., shared or individual car use) – all of which may be shaped by public policy (e.g., congestion charges), cultural norms (e.g., bicycle use in European vs US cities) and individual choices (e.g., when to drive or cycle). Circular approaches, such as enabling design for recycling and reuse, can improve the efficiency of technology, but cannot escape the other factors in the IPAT equation: population and affluence could still drive up impacts.

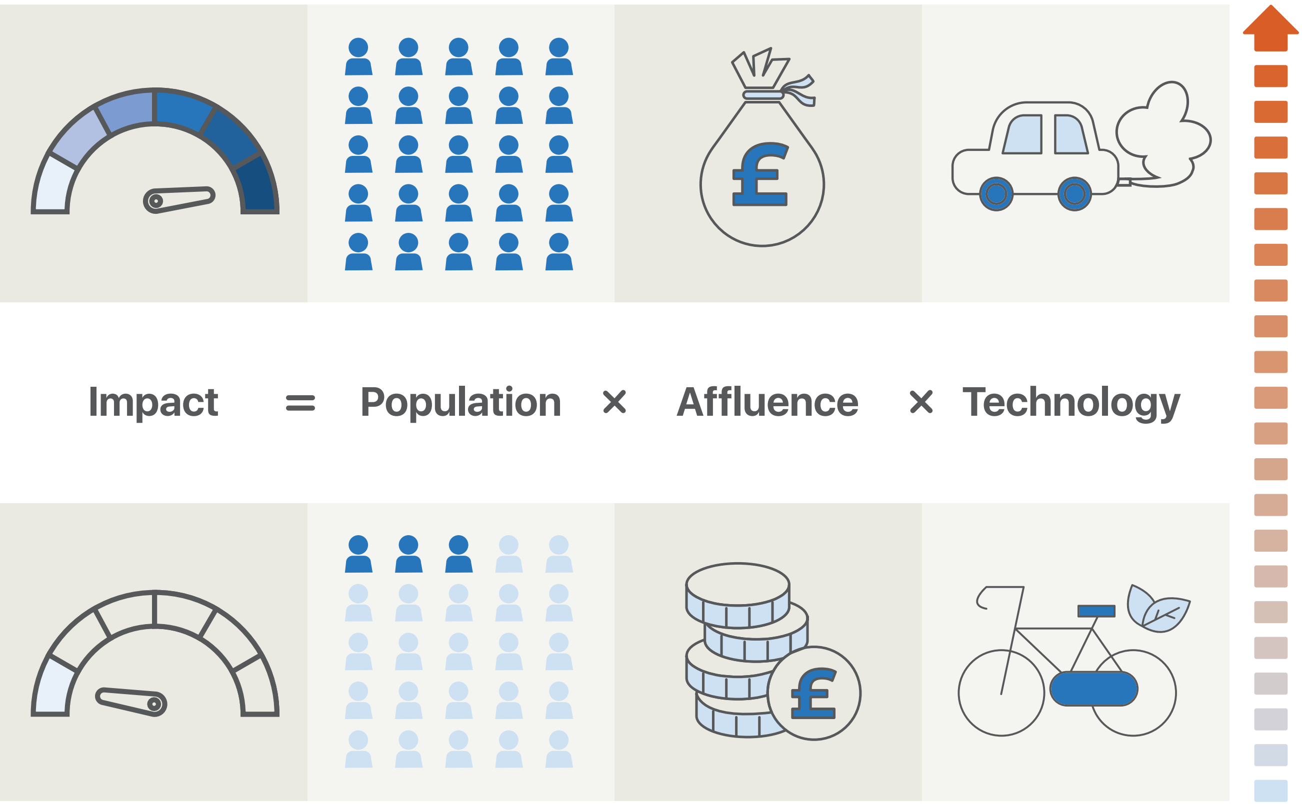


Figure 10 The IPAT equation. The impact of human activity depends on the number of people, their affluence and the efficiency of technology.
Source: authors

Industrial ecologists have estimated the contributions of new technologies and behaviour to climate change mitigation, such as new building materials and a shift to smaller dwellings, lighter vehicles and shared mobility services (IRP 2020). A study on China applied the IPAT equation to emissions from food and found that technological improvements have reduced emissions from food consumption. However, the study also found that further reductions will likely need to focus on dietary changes (He et al. 2021).

THE SOCIAL EMBEDDEDNESS OF INDUSTRIAL SYMBIOSIS

The exchange of waste as a resource in industrial symbiosis (see Insight 1) happens more often when companies are geographically close. However, such exchanges also depend on the socio-cultural closeness or "mental distance" between firm managers. A study by Ashton and Bain (2012) found that managers in industrial districts in Nanjangud, south India, shared the same view of waste as a potential resource and operated within a culture that sees the reuse of waste as a norm. Other factors that potentially affect symbiosis are economic costs and benefits as well as interpersonal ties, the frequency of communication and mutual trust between participants.

Insight 10

THE FUTURE IS UNKNOWN BUT MAY BE ANTICIPATED

Understanding the future impacts of innovative products, services and technologies is critical to supporting the circular economy. Such foresight can support policymaking, product design, early-stage research and technology scale-up. Industrial ecologists use scenario modelling to investigate, for example, the potential impacts of electric cars (Figure 11). Pauliuk et al. (2021) performed a dynamic material flow analysis to study residential buildings and passenger vehicles on a global scale. The authors modelled scenarios for various technological developments (increased yields, light design, material substitution, extended service life and increased service efficiency, reuse and recycling) and how these could potentially influence energy use and material flows.

Ex-ante/prospective life cycle assessment explores the potential environmental impacts of emerging technologies that have not yet achieved full-scale production (van der Giesen et al. 2020). A prospective life cycle assessment of ethylene production – the raw material for most plastics – showed how the energy and greenhouse gas emission reduction benefits of five emerging technologies depend on factors such as technology adoption options (e.g., retrofit or new construction) and the future market for natural gas (Yao et al. 2016). Other studies have shown significant differences in the environmental impacts of laboratory scale and scaled-up (e.g. pilot/industrial) production (Piccinno et al. 2016), which is a critical factor for the reliable assessment of the environmental impacts of emerging technologies and systems for the circular economy.

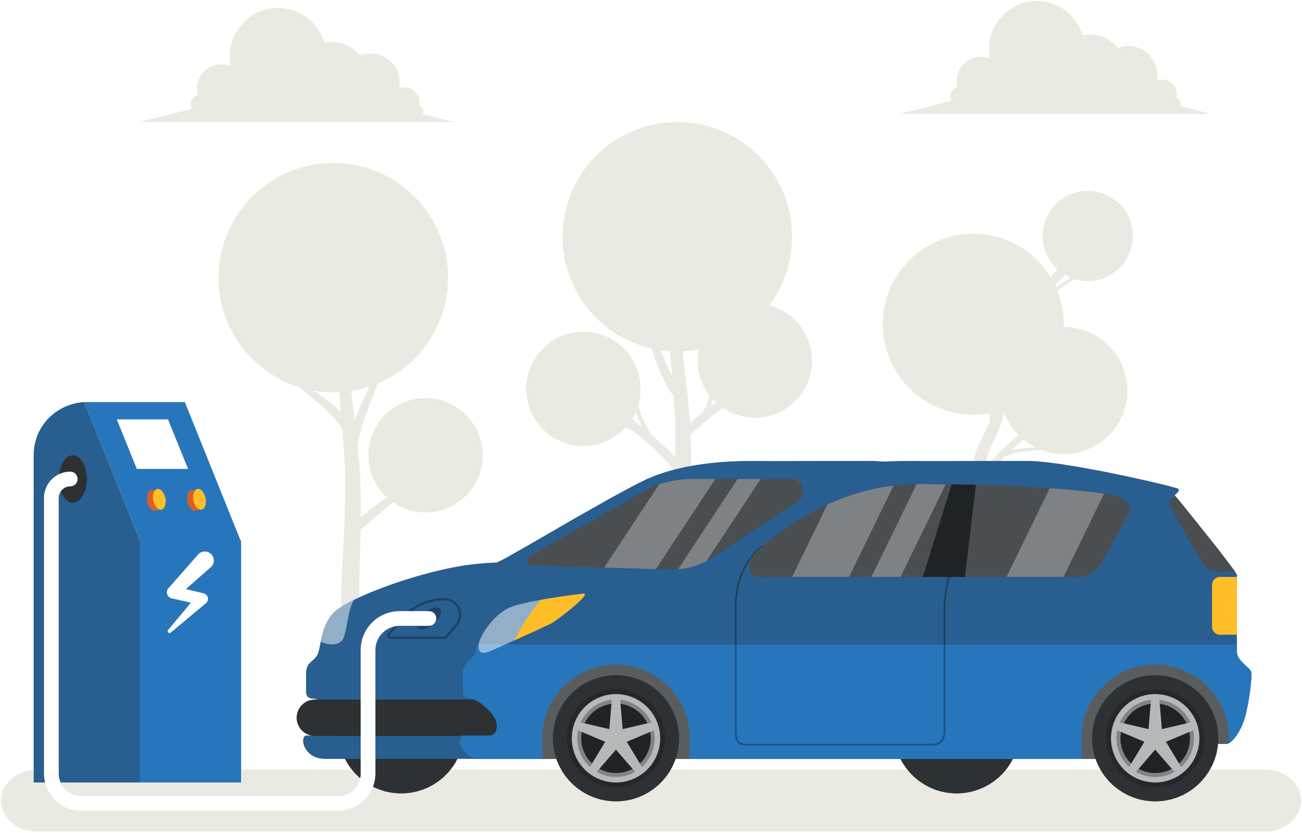


Figure 11 The impact of future technologies depends on how related technologies develop. The benefits of electric vehicles are greater when the future electricity system is renewable since this generally has a lower environmental impact than fossil electricity generation.

Source: authors

ANTICIPATING CONTAMINATION

Steel is widely recycled, which saves energy and reduces the need for iron ore. However, the more often we recycle, the more contaminants accumulate in steel because the recycling process is imperfect, causing quality problems. An analysis by Daehn, Cabrera Serrenho, and Allwood (2017) shows that copper concentration is likely to rise until the steel becomes unrecyclable. Early intervention can prevent such problems, including through improvements in recycling strategies and processes, product manufacturing and product design. For instance, copper contamination can be reduced when the copper wiring in cars can be easily separated before shredding and recycling.

METHODS

This white paper was developed by an international expert group of members of the International Society for Industrial Ecology. They developed and formulated the 10 insights based on discussions held between September 2021 and November 2022. The group started in 2020 as a bottom-up initiative by ISIE members to facilitate knowledge exchange and greater engagement between industrial ecologists and circular economy stakeholders.

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