The circular economy and intelligent decentralization, nanotechnologies and materials, minerals and mining**

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The circular economy, materials, minerals and mining (M3), nanotechnologies and intelligent decentralization are inseparably intertwined, which means that future economic strategies needs to take a holistic or systems approach. COVID-19 has inverted the notions of productive and essential activities, and brought to light the shortcomings of the linear silo approach in academia, industry and public administration, which today often predominates for reasons of short-term efficiency and checks and balances.

1. Introduction

Circularity has always been the principle governing nature. A circular society making the best use of accessible resources is as old as mankind, as is the circular economy associated with poverty—use it up, wear it out, make it do or do without.

Less than a century ago, the modern circular economy started when industrialized countries had accumulated sufficient stocks of manufactured objects in markets near saturation. This is the circular economy of abundance, which depends on the motivation of owner–users to look after, and care for, their belongings, while a circular economy of scarcity and poverty still exists in less industrialized regions of the world.

1.1 Circular society and circular economy

A sustainable and resilient circular society is about *maintaining* existing wealth in the form of .value and utility of stock or capital:

- **natural** capital (the bioeconomy: land, water, forests, animals and plants, biodiversity; life sciences);

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- **human** capital (people, labour, health, wellbeing and intangible assets such as skills, expertise, knowledge, creativity);
- **cultural** capital (monuments, landscapes, music and traditions, such as *kintsugi* (golden sewing) in Japan);
- **manufactured** capital of visible objects (infrastructure, buildings, equipment, goods, components and materials) and of invisible assets (data, embodied resources, liability);
- **financial** capital.

The objective of a circular industrial economy is to maintain the value and utility of stocks of objects, and the value and purity of stocks of atoms and molecules, for as long as possible. Compared to the linear industrial economy based on added value created by rapid throughput, this approach creates local jobs, prevents waste, reduces resource consumption and increases resource efficiency.[1] A circular industrial economy is focused on *manufactured* capital and driven by economics, innovation and competitiveness (Figure 1). As most resources cost money, wasted resources are wasted money. Managing wasted resources (= wasted money) does not make financial sense, whereas innovation to prevent wasted resources is profitable.

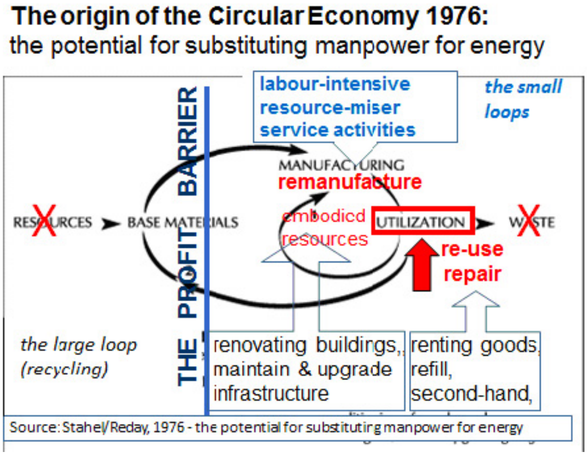

Figure 1. The first vision of a circular industrial economy (1976).

The economic focus on *human* capital since Adam Smith has been on productive labour,[2] defined as any work that fixes itself in a tangible object. Unproductive labour is any work where the value is consumed as soon as it is created. COVID-19 has turned Adam Smith's hierarchy of productive and unproductive labour upside down—"unproductive" labour in essential services has turned out to be the precondition for productive labour (the absence of empathy from unproductive labour—solitude—can even kill). The mainstream economy ignores the opportunities of operational life extension services in the circular economy (which seeks to maintain, not create, tangible objects), and neglects *essential services* often carried out by specialized,[3] sometimes even illegal, workers,

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[1] Stahel, W.R. & Reday, G. *Jobs for Tomorrow, the Potential for Substituting Manpower for Energy*. New York: Vantage Press (1981).

[2] Smith, A. *The Wealth of Nations*. London: William Strahan (1776).

[3] The French term *ouvrier spécialisé* is very honest in meaning: an unqualified person who can only do one job.

such as emergency services and security, healthcare and cleaning, agriculture; postmen, logistics and sales staff and operation and maintenance workers, many of them in unproductive jobs with low wages and low social recognition, in the spirit of Adam Smith's conception.

COVID-19 has switched the societal attitude from "daring" to produce added value to "caring" to maintain existing value. It remains to be seen whether this will continue and incite a shift from the hitherto dominant linear industrial to a circular industrial economy in industrialized regions enjoying a society of physical abundance.

1.2 Intelligent decentralization

The lockdown caused by the political decision to reduce the impacts of COVID-19 showed pitilessly that the competitiveness of today's superefficient linear industrial economy had close to zero resilience, lacked sustainability and reminded us that:

- globalization to achieve maximum economy of scale goes hand-in-hand with maximum diseconomy of risk, where the weakest link in a (supply) chain determines its strength;
- local production and supply of essential goods, such as food, medicines and medical equipment, and of essential services, continue to function in a complete lockdown;
- the use-intensity of manufactured stocks may be affected but not the quality and quantity of the stocks themselves;
- if we stay at home, the air is clean and the sky is blue.

The circular economy of objects forms part of a growing trend of intelligent decentralization; repair and reuse services are best carried out locally where clients and their objects are situated. The nascent circular economy of atoms and molecules will also be regional, with new players acting as resmelters and fleet managers of molecules.

In future, decentralized production of, for example, pharmaceuticals could also become the preferred corporate strategy because it reduces risks in logistics, and it facilitates high-volume production in the case of, for instance, an epidemic (according to the CEO of Roche in Basel). Decentralization also applies advantageously to nanoproducts such as carbon nanotubes (CNTs) that cannot be stored or transported without severe degradation, and short-lived tracer elements used in medical examinations. Local by definition are the services of the business models of the *performance economy*, where economic actors sell objects as a service, such as railway journeys, retaining ownership and liability of the objects during the full product life.

1.3 Nanotechnologies

At the nanoscale, the properties of materials may differ significantly from those at a larger scale. The efficiency of a process may increase exponentially with the reduction in weight and size, and as the ratio of volume to surface changes radically. The more efficient a component, the higher the sales price it commands—this is the logic shared with the performance economy and true for mechanical, chemical, medical and other processes as they approach the nanoscale. Nevertheless, it has been recognized for some time that problematic for human health are the ubiquitous nanoparticles, which accumulate in soil, air and water, originating from

- friction between parts in machinery, including the wear and tear of road tyres;
- consumer goods, such as foodstuffs and cosmetics;

- durable goods, such as stain-repellent textiles and electronic devices;
- coatings of windows and curtain walls in buildings and automotive (metallic) paints.

A 2004 report by the UK's Royal Society and Royal Academy of Engineering recommended that nanoparticle production be continued, that more formal research be undertaken into the hazards and exposures, and that nanoparticles made from familiar elements and compounds be treated as new chemicals.[4]

1.4 Issues of intersection (Figure 2)[5]

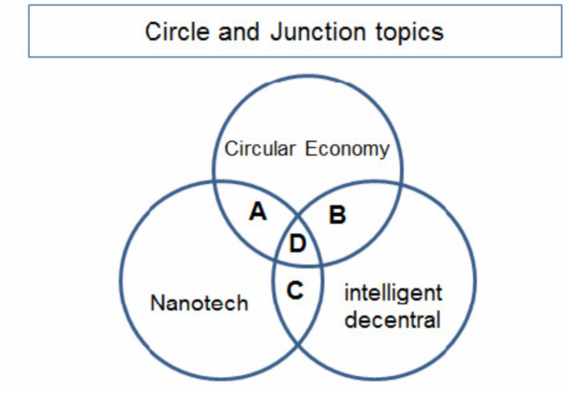

Figure 2. Relevant topics and their intersections.

- A the principle that less is more, and more efficient;
- B local additive manufacturing enables wasteless spare parts on demand;
- C Carbon nanotubes (CNT), nanostructured microreactors;
- D the performance economy is part of the circular economy and profits from decentralized services and nanotechnologies.

The circular industrial economy is one of the strategies of the performance economy—maintaining performance over time—while the two other strategies of the performance economy—producing performance and selling performance—are its most sustainable and profitable business models, fully exploiting the opportunities of the circular industrial economy.

2. The role of materials, minerals and mining (M3) in the circular industrial economy

Half the CO_2 emissions and 90% of biodiversity loss and water stress today comes from the extraction and processing of materials.[6] A reduction in material extraction, a more efficient use of materials and a circular M3 sector would therefore substantially improve its sustainability.

The construction and building industry is the biggest consumer of materials, and regional by nature because most of its resources—sand, gravel, cement and water—are materials with a

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[4] *Nanoscience and Nanotechnologies: Opportunities and Uncertainties*. London: Royal Society and Royal Academy of Engineering (2004).

[5] *The Junction of Health, Environment and Bioeconomy Report*. Brussels: DG JRC (2015) https://ec.europa.eu/research/foresight

[6] *Global Resources Outlook*. International Resource Panel (2019) https://www.resourcepanel.org/reports/global-resources-outlook

low value per weight ratio. Cement producers are among the world's biggest CO_2 emitters,[7] and cement is a material that today cannot be recovered for reuse. But buildings are highly suitable for receiving operational life extension services, including upgrading of their envelope and technical equipment inside.

In industrialized countries, a longer operational (service) life of objects reduces the demand for resources (materials, energy and water) in manufacturing and reduces the volumes of transport, end-of-service-life objects and wasted resources (see Fig. 1). At first sight, a circular economy will negatively impact the M3 sector. However, a second look at the novel strategies and business models of the circular industrial economy shows that through innovative new materials, components and systems to upgrade existing stocks and increase the circularity of production, the M3 sectors could profit from the circular industrial economy—these sectors could even move into the driving seat.

On the other hand, in less industrialized countries with an insufficient stock of infrastructure, buildings and goods, and people still stuck in a circular economy of scarcity or poverty, the linear industrial economy will first have to produce sufficient stocks for a circular economy to flourish.

For single-use goods, such as food, pharmaceuticals, toilet paper and surgical masks, storage is necessary to buffer production shortages. The size of this storage is correlated with the degree of decentralization of the good's production. Yet, the design and production of—for example—reusable masks, including subjecting them to washing or sterilization to achieve reuse, would be more sustainable.

2.1 The seven challenges *of a mature circular industrial economy (Fig. 3):*

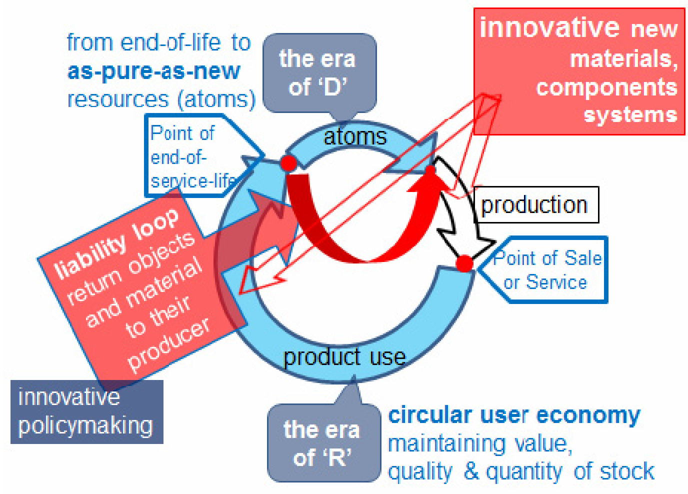

Figure 3. View of a mature circular industrial economy.

1. The era of "R" ("re-") extends the service life of objects through the reuse, refill, repair, remanufacture and reprogramming of objects and other goods, which reduces mining, resource consumption and waste volumes (Figure 1). The desire of owner–users to maximize the use-

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[7] A technology developed by Solidia Technologies reduces CO_2 emissions from concrete production by up to 70%. In 2020, LafargeHolcim signed a framework agreement with Solidia Technologies for long-term cooperation until at least 2025.

value of objects, caring and trust are the drivers of the era of R. R innovation pioneers are constantly conquering new domains, such as space. SpaceX with its reusable Falcon 9 rockets and Dragon capsules, and Northrop Grumman with its space mission-extension vehicle, which succeeded in returning aging satellites back into service, are examples.

2. The era of "D" *de*links materials, using new processes to depolymerize, dealloy, delaminate or devulcanize materials, or decoat objects, in order to recover atoms and molecules for reuse. The era of D maintains the value and purity of the elementary constituents (atoms, molecules, nanoblocks) and includes deconstructing infrastructure and buildings; it uses different technologies from processing virgin ores but nevertheless represents a major opportunity for the materials, minerals and mining sectors.

Society long overlooked the fact that the Anthropocene incorporates an "immaterial" aspect of societal responsibility for man-made (synthetic) materials unknown to nature's circularity. This is the formidable policy challenge.[3]

3. The full producer liability loop is a policy innovation, according to which objects made of synthetic materials are returned to their producers. It will lead to product designs aimed at recovering the highest material values and minimizing liability in corporate financial accounts.

4. Spreading circular economy knowledge to all class- and boardrooms, SMEs and parliaments: primarily a communication task. Knowledge motivates action: repairing a pair of jeans instead of buying anew saves 11,000 litres of water! But to convince policymakers, "evidence might be there, but unless there's a practical solution, the science will be ignored".[8] A practical solution is offered by the circular economy.

5. Innovative materials, components and systems derived from materials and systems sciences focused on "circular" physics, chemistry and metallurgy are needed to upgrade existing stocks and produce innovative circular objects.

6. The performance economy—producing and selling performance, goods and atoms as a service—opens up new business models: producing performance is especially relevant for exploiting opportunities in nanotechnologies.

7. Measuring the invisible water, energy and material resources consumed, and CO_2 emitted, from mine to point of sale—an accountancy task. These invisible entities remain embodied in manufactured objects and in future may be measured and registered in, for instance, product passports (see also Fig. 5).

The greatest interest for the M3 sectors are hidden in challenges 2, 5 and 6.

2.2 The era of D—challenge 2—is a legacy of the Anthropocene, when science enabled mankind to uncouple its material needs from nature, to create "synthetic" materials and harvest energies unknown to Earth.[9]

The era of D is controlled by "managers of used resources", or recyclers, the owner-managers of end-of-service-life objects. Their options to maintain the highest value are hampered by inept

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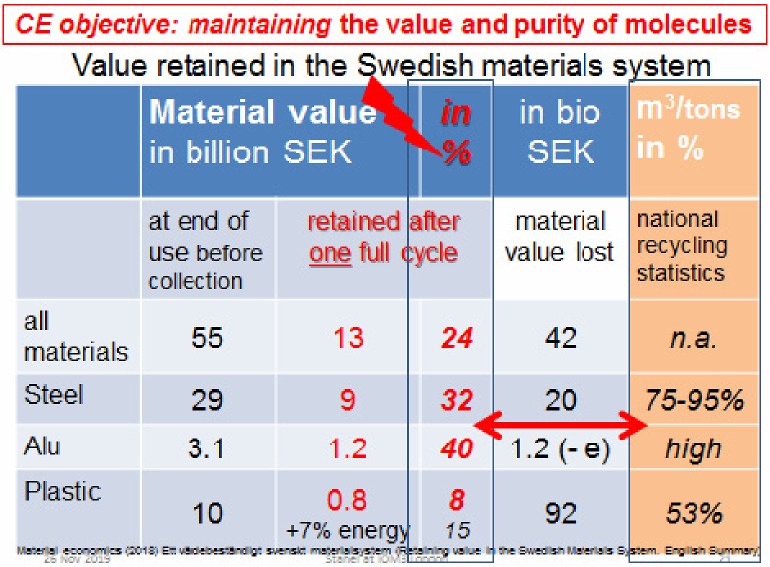
[8] Dr Marcia McNutt, President of the U.S. National Academy of Sciences, quoted by Richard G. Newell, President and CEO, Resources for the Future, Christmas 2018.

[9] For example, used objects made of porcelain, manufactured from natural material, can be ground and the material reused.

legislation, the second law of thermodynamics and missing tools, pushing them to incinerate and downcycle many used manufactured objects, for lack of:

- **access to appropriate technologies** to recover atoms and molecules (in the era of D);
- **affordable methods** of collecting clean fractions of materials and of disassembling objects;
- **legislation** allowing them to resell components and goods at the highest price for reuse, repair or remanufacture (in the era of R).

In each recovery cycle, these constraints result in a great loss of purity and value, estimated at between 66 and 75% of economic value in a recent study for the Swedish Recyclers' Association (Fig. 4).[10] Present national recycling statistics are based on waste tonnage or volume and refer to their diminution, not economic value retention.



CE objective: *maintaining* the value and purity of molecules

Value retained in the Swedish materials system

	Material value in billion SEK		in %	in bio SEK	m^3/tons in %
	at end of use before collection	retained after one full cycle		material value lost	national recycling statistics
all materials	55	13	*24*	42	*n.a.*
Steel	29	9	*32*	20	*75-95%*
Alu	3.1	1.2	*40*	1.2 (- e)	*high*
Plastic	10	0.8 +7% energy	*8* *15*	92	*53%*

Material economics (2018) Ett vädebeständigt svenskt materialsystem (Retaining value in the Swedish Materials System. English Summary)

25 Nov 2019 Stahel at IOM3 London 21

Figure 4. Value retained after one full material (re)cycle, for different materials.[10]

For some plastics (synthetic polymers), economic actors have taken control to recover their molecules for reuse, for example through take-back and buy-back of their used objects and molecules:

- end-of-service-life tags or machine-readable tracer recycling technology. E.g., Unilever recovers its packaging for de- and re-polymerization using tracer elements;[11]
- Interface has for two decades been recovering its used carpet tiles in order to de- and re-polymerize for reuse the PA 6 and 66 (nylon) molecules;
- Plasto Norway has started to recover its used fish farm equipment in order to de- and re-polymerize for reuse its HDPE (high density polyethylene) molecules;

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[10] Material economics. *Ett värdebeständigt svenskt materialsystem* (retaining value in the Swedish materials system). Unpublished contract research (2018).

[11] https://www.circularonline.co.uk/news/disruptive-tags-trace-recycling-technology-launches

- TRS (tyre recycling solutions) has started to recover steel wire, carbon black and PU (polyurethane) from used tyres and sells the molecules to a tyre manufacturer to produce new tyre treads.

With regard to metals, M3 companies seizing control of end-of-life objects from recyclers might be able to recover a large part of the lost value with existing technology, helped of course by the very convenient phenomenon of ferromagnetism.

2.3 Circular materials and systems sciences—challenge 5—can prevent a repetition of the synthetic waste creation of the early Anthropocene, which created a huge unwieldy legacy but did progress in:

- nuclear physics—developed bombs, controlled nuclear energy[12] and radiomedicine;
- chemistry—developed polymers (plastics), customized chemicals and pharmaceuticals;
- metallurgy—invented a multitude of metal alloys, such as stainless steels.

The M3 sector could now pick up the scientific challenges thrown up by the early Anthropocene to innovate materials, molecules and processes based on circular physics, circular chemistry and circular metallurgy, and gain international competitive advantages by exploiting techno-commercial inventions of the performance economy, such as rent-a-molecule. Examples:

- The carbon nanotube (CNT) is a highly innovative nanomaterial that could be made from a resource presently in excess in the terrestrial atmosphere. CNTs are lighter and stronger than steel and can also conduct electricity well. Methods are being developed to spin CNTs into usable components, such as thin sheets made of trillions of individual CNTs. The resulting ultralight material would weigh a few grams per hectare and could be used in medical and technical applications, and possibly even in construction.
- Early examples of circular energy are:
    - geothermal energy, sufficiency solutions, energy savings, -recovery and -efficiency;
    - hydrogen fuel cells: Japan's national energy strategy and a growing number of applications in Norwegian express ferries, German regional trains, Switzerland (Hyundai lorries, Stadler trains exported to California) and South Korea;[13]
- Early examples of circular metallurgy have been described in the literature. However, "smart" materials that can easily be reused are of no economic interest to the present linear industrial economy focused on low-cost mass production. A shift to the performance economy could open up markets for these innovations (see §5), such as:
    - a composite powder that can be pressed into any form and, when magnetized, becomes an extremely powerful permanent magnet. After use, it can be demagnetized by grinding it back into powder for reuse;[14]
    - metallic (i.e., electrically conductive) window glass (i.e., transparent).

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[12] The two Voyager spacecraft, launched in 1977, are both powered by small nuclear reactors. They have left the solar system, entering interstellar space, and continue functioning.

[13] A "Clean Hydrogen Alliance" was successfully launched by the European Commission in July 2020, with broad backing from EU member states and companies involved in the hydrogen value chain. A prior Fuel Cell and Hydrogen Joint Technology Initiative (JTI) launched in 2008 by the European Commission and an association of European fuel cell manufacturers and hydrogen producers had not taken off.

[14] Stahel, W.R. *The Performance Economy* (2nd edn), p. 32. Basingstoke: Palgrave Macmillan (2010).

- Early examples of circular chemistry are:
  - Polydiketoenamines (PDKs), polymers whose manufacture requires low energy and water consumption, and which are 100% recoverable as pure monomers for reuse;[15]
  - self-destroying polymers for drug delivery and scaffolds for 3D printing;[16]
  - Carbon capture and utilization (CCU); for instance, Climeworks converts CO_2 extracted from the air into solid carbon in the form of high-purity carbon black.

Scientists are also making progress in biochemistry, which is of potentially circular nature:

- architectured (or tailored) molecules and synthetic biology;
- microbes to digest plastic waste,[17] and developing acid-triggered, acid-generating and self-amplifying degradable polymers;[16]
- a mutant bacterial enzyme, created by scientists from an enzyme found in compost heaps of leaves, processes plastic bottles to elementary chemical building blocks, which can be reused to make high-quality new bottles;[18]
- German researchers discovered a bacterium that feasts on polyurethane.[19] Earlier work had shown that wax moth larvae—usually bred as fish bait—can eat up polythene bags;[20]
- "Coldzymes", psychrophilic enzymes from the high Alps, enable washing without heating the water, reducing the electricity consumption of domestic washing machines by 90%;
- traditional vessels made of brass or copper, until recently relegated to decorative functions, have been used to collect and store water because they kill bacteria by copper ions leaching from the walls.

Other potential applications of synthetic biology in the economy may be outside what is usually considered to be the remit of the M3 sector, such as delignification of wood (high-strength "wood" modified using enzymes).[21]

2.4 Challenge 6, The performance economy, producing, selling and maintaining performance over time, such as goods, molecules and atoms as a service

In the performance economy, owner-fleet managers of objects and molecules are in control to profitably exploit efficiency, sufficiency and systems solutions, in addition to the R and D eras of opportunity of the circular industrial economy. By retaining ownership of stocks of strategic materials, fleet managers selling performance also gain corporate and national resource security:

> *Today's objects are the resources of tomorrow, locally available at*
> *last year's resource prices.*

Rent-a-molecule business models give corporations stability and prevent pollution and toxic waste, and are promoted by UNIDO in Africa for health reasons. Business models of

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[15] Brett Helms' Research Group https://foundry.lbl.gov/helmsgroup

[16] Miller, K.A. et al., Acid-triggered, acid-generating, and self-amplifying degradable polymers. *J. Am. Chem. Soc.* **141** (2019) 2838–2842.

[17] https://www,surrey.ac.uk/news/new-study-could-revolutionise-way-we-recycle

[18] Carbios, the company behind the breakthrough, has partnered with major companies including Pepsi and L'Oréal.

[19] https://www.theguardian.com/environment/2020/mar/27/scientists-find-bug-that-feasts-on-toxic-plastic

[20] https://www.theguardian.com/science/2017/apr/24/plastic-munching-worms-could-help-wage-war-on-waste-galleria-mellonella

[21] Li, T. et al. A radiative cooling structural material. *Science* **364** (2019) 760–763.

"selling performance" (also known as product–service systems or servitization) are already used by solvent producers, common among paint manufacturers, and can be applied to many other industrial sectors. Economic actors selling performance:

- guarantee results (pharma industry) or retain ownership of infrastructure and objects and embodied (invisible) resources;
- internalize the liability for all costs of risk and of waste;
- save transaction and compliance costs compared to virgin material producers;
- gain long-term resource supply security;
- can give clients a function guarantee of uninterrupted services.

Revenues of mining companies could profit from a shift to the circular economy; material producers could even move into the driving seat of the economy by producing performance and selling the performance materials as a service. We already have some examples:

- ceramic slide-gate exchange services for the steel and iron industry pay per use;[22]
- DuPont performance coatings managing clients' paint shops pay per finished part;[23]
- Dow rents solvent molecules (through its subsidiary SafeChem);
- the composite powder mentioned in footnote 14 would probably be leased rather than sold if commercialized by the Cookson Group.

Applied to complex products, these business models could create a chain reaction as manufacturers of objects that were traditionally sold to customers must now lease them to users in order to be able to guarantee the return of the smart material to its producer.

Other examples include energy management services, Amory Lovin's Negwatts, and the novel concept of molecule leasing.[24] Rolls-Royce and GE are pioneers in selling performance; "power by the hour" of jet engines is an established business model. By combining operational leasing contracts with permanent monitoring and reporting of engine performance via satellite, preventive maintenance and preventive engine replacement as well as spareless repair methods enable producers to retain ownership of strategic materials, in cooperation with resmelters of sorted material fractions as service providers.

3. The circular industrial economy and intelligent decentralization

By their nature, reuse, refill, reprogram, repair and remanufacture activities of the circular economy are best done locally; i.e., where the clients and their goods are located. Moving information instead of goods avoids duplication of transport and the ensuing environmental burdens. Remanufacturing and additive manufacturing by local robots to produce spare parts even enables the reindustrialization of regions based on management of existing physical stocks and the often rich industrial patrimony of a region.

Intelligent decentralization is a novel general and seemingly inexorable trend across the economy, facilitated by IT networks, data exchanges, additive manufacturing and innovative

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[22] Stahel, W.R. *The Performance Economy* (2nd edn), p. 117. Basingstoke: Palgrave Macmillan (2010).

[23] Footnote 10, p. 134.

[24] Hagan, A.J. et al. The license to mine: Making resource wealth work for those who need it most. *Resources Policy* (in press) https://doi.org/10.1016/j.resourpol.2019.101418; https://www.sciencedirect.com/science/article/abs/pii/S0301420717305445

SMEs. This trend has been strongly and advantageously reinforced by travel restrictions linked to COVID-19, notably:

- **home** working, banking, schooling, cooking;
- **local**
    - essential services (health, social care, safety and repair);
    - circular society initiatives, such as repair cafés, cafés for medical doctors (MDs);
    - medicines-on-demand;[25]
    - energy production: geothermal, photovoltaic (PV) and microhydroelectricity, waste-to-biogas, floating aquatic PV-to-hydrogen plants;
    - production of carbon nanotubes (CNTs) and short-lived tracer elements needed in nuclear medicine;
- **mobile** repair **workshops** for outdoor clothing by Patagonia, mobile plants to can tomatoes on farms by Arcelor;
- **micro**-breweries, -bakeries, -credit and -insurance; **crowd**-mapping, -finance and -campagning;
- **urban**
    - mining;
    - farming;
- **regional** business innovations:
    - direct sale of locally produced seasonal food;
    - closed water cycles, from waste water to drinking water (NEWater in Singapore);
    - promotion of loss prevention, sufficiency and systems solutions;
    - AI, robots and additive manufacturing (3D printing); unlike labour, robots have similar prices worldwide. Other cost factors such as risks now dominate and favour decentralized industrial production.

COVID-19 has shown the limits of a globalized linear industrial economy, crucially in producing single-use goods for essential needs, such as food, pharmaceuticals and face masks. Regionalized production and the development of reusable alternative goods, where feasible, would create a more resilient society. The production of globally manufactured objects, for which there are now stocks everywhere, such as cars or airplanes, was not regarded as essential. The simultaneous abrupt halting of their manufacture and use did not impact our wealth and wellbeing except for the job losses in the directly impacted supply chains.

The jobs involved in maintaining the stocks of the circular economy through the reuse and repair of objects, for instance, were much less affected and regarded as essential—plumbers, electricians, car repair workshops in addition to caring for human capital: medical doctors, other health workers, care workers and janitors (caretakers). COVID-19 thus has shown the feasibility of a shift of focus from daring to caring, from global to regional, from production to services—at least temporarily, confirming the feasibility of repair workshops that were as much part of mediaeval cathedrals as they are now of the Forth and Golden Gate bridges (see Fig. 5).

Developing user-friendly objects through modular design processes, much greater use of standardized components, and novel repair processes such as spareless repairs and dedicated repair spares, would enormously increase the number and level of qualification of jobs in the era

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[25] Arnold, C. Medicines on demand. *Nature* **575** (2019) 275–277.

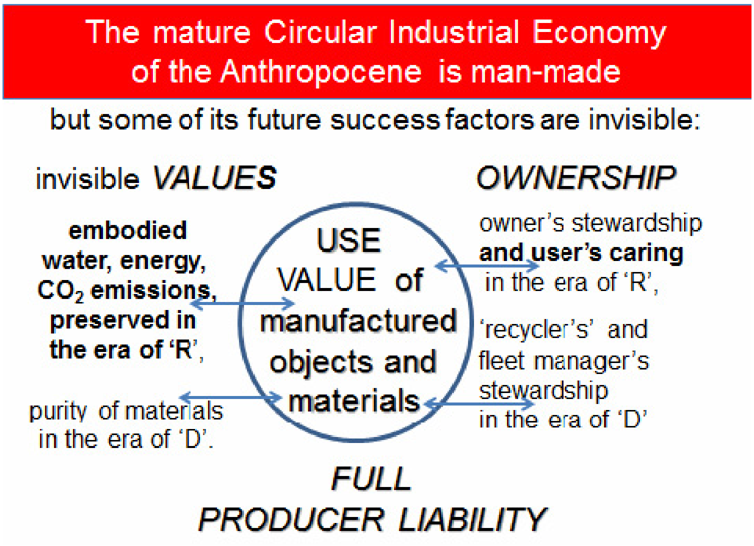

Figure 5. Values, ownership and liability in a mature circular industrial economy.

of R—and save money. Remanufacturing complex technical systems, such as trains or aircraft, reduces costs by 80%—and uses small amounts of material. *In situ* remanufacturing of rail heads is actually better than new—achieving a tolerance of 1/100 millimetre, versus 1/10 millimetre for new rails—at half the cost of rail replacement.

Technological upgrading of stocks speeds up progress: the world's first commercial all-electric plane is a six-seater 1964 de Havilland Twin Otter seaplane remanufactured and converted by its Vancouver owner, Harbour Air, in 2019.

Some nanotechnology applications, such as carbon nanotubes (CNTs), cannot be separated out if intermingled or have a short life, such as the ^{18}F isotope of fluorodeoxyglucose (FDG) used in positron emission tomography, but decentralized production operations situated near the places of demand overcome the problem that the products cannot be stored or transported. Small quantities of chemicals can be safely produced in tiny nanostructured locally available equipment where they are needed, making the transport of hazardous substances over longer distances superfluous and favouring high-tech regional economic development.

Geothermal energy and concepts such as Japan's hydrogen economy may well lead to a regionalization of energy production and change the structure and function of the electricity grid.

4. Circular economy and nanotechnologies

To reiterate, the objectives of a circular industrial economy are to maintain the value and utility of stocks of objects, and the value and purity of stocks of atoms and molecules for as long as possible, and to prevent wasted resources.

Nanotechnologies enable extremely long service-lives of components such as nanopolished bearings. However, long-life components that can easily be reused are of no economic interest in the present linear industrial economy focused on cheap mass production. But the winds are changing: SKF, a major producer of bearings, and Grundfos, a major pump manufacturer, have started to take back, remanufacture and remarket their products. A shift to the performance economy will broaden the markets for these innovative business models in the era of R (see §5).

In the era of D, which deals with materials, an equivalent strategy is needed, for instance for waste water streams. In pilot plants, a few minerals, such as gold and phosphorous, are today recovered from waste water, in addition to waste heat. The 2016 Swiss legislation to protect natural waters[26] limits the input of soluble organic trace substances; that is, organic micropollutants present in low concentrations that can affect aquatic life (e.g., the active ingredients of medicines, pesticides and other biocides, food additives, industrial chemicals such as corrosion inhibitors and flame retardants, and natural and artificial hormones). These substances have to be removed either by adding ozone or activated carbon to the waste water, but are not recovered thereafter.

The legislation stipulates that the "success" of these processes is measured on the basis of twelve substances (ten active pharmaceutical ingredients and two corrosion inhibitors), which on average must be eliminated by 80%. The assumption is that if this is done, a large proportion of all trace substances will be removed.

The situation is different with insoluble particulate substances such as microplastics or nanoparticles, partly originating in the run-off water from roads when it is channelled through waste water treatment plants; at present there are no specifications regarding their elimination. For the most part, these substances adsorb onto the activated sludge in the biological stage of the treatment plants. If a filter is added downstream, as is quite usual, more microplastics at least could be captured. It is an open challenge to *recover* the atoms and molecules of these captured micropollutants, microplastics and nanoparticles—or, better still, prevent them from getting into the environment in the first place.

Worldwide, Singapore today is the only nation-state with a waste water treatment system that enables waste water to be reused for drinking purposes: the NEWater.

5. The performance economy and nanotechnologies[27]

Technological progress in manufacturing imposes changes in the belief structure of the mainstream economy. Nanotechnologies teach us that the smaller a product, the more efficient it can be and the higher the sales price it commands—fulfilling the very definition of the performance economy.

Nanostructured microreactors[28] have a strong performance focus:

- Chemicals are produced in batch or flow processes. If these chemical reactions produce large quantities of heat, their control can be difficult or, on an industrial scale, even become dangerous. If the reaction accelerates, the reactor can overheat and explode. Controlling the heat is easier in the case of small, thin tubes or large heat-absorbent surfaces. Microreactors scale out similarly to supercomputers, which consist of thousands of parallel microprocessors.
- The DSM Fine Chemicals company succeeded in building the first suitcase-size parallel

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[26] Swiss *Gewässerschutzgesetz* (GSCHG), revised in 2016.

[27] Examples without reference in this and the previous section have been taken from Stahel, W.R. *The Performance Economy* (2nd edn). Basingstoke: Palgrave Macmillan (2010).

[28] Iles, A. Microsystems for the enablement of nanotechnologies. *Nanotechnol. Perceptions* **5** (2009) 121–133.

reactor capable of treating 1300 kg of raw material. The resulting fine chemicals are of perfect quality, which was impossible to achieve until now. In addition, the process has a very high safety record as only few litres of chemicals are in the microreactor at any given time. If the process starts to overheat, the raw material input is replaced by water.

- Many research centres have built and are using nanostructured microreactors. Clariant, a Swiss speciality chemical company, uses this technology in production processes and has found another advantage: a considerably higher purity and thus performance of colour pigments.
- Intelligent parallel working nanostructured microreactors instead of large centralized reactors also reduce packaging, shipping and storage needs. This might further spread the "workshop in the factory concept" of selling performance, already common with paint manufacturers.
- Nanostructured chemical microreactors have opened new and safer production methods. Relative to their individually tiny volume, microreactors have a huge surface to absorb heat or free molecules produced in chemical reactions. As chain reactions are now easier to control, substances and processes hitherto considered off limits can be exploited; mixing oxygen and hydrogen to produce water in space could be such an application.

"Lab-on-a-chip" systems are another new concept,[29] with a design similar to that of electronic chips. Minute quantities of fluids circulate instead of electrons; nanocanals, valves and reaction chambers replace transistors. A team from Stanford University and the University of California has succeeded in producing the radioactively labeled substances (FDGs) used in positron emission tomography in a lab-on-a-chip. The traditional equipment needed to produce these substances fills a whole room.

Health is a domain where patients expect nowadays performance or money-back guarantees; and professional liability insurance has therefore become mandatory for medical doctors in many countries. Some pharmaceutical companies now provide such a guarantee for expensive cancer treatments. Furthermore, nanostructured microreactors producing medicines could eliminate the need for patients to travel to central hospitals, improving overall performance and productivity.

Toto Ltd in Japan has developed a possible way of reducing the side effects of cancer drugs by using the photocatalytic properties of titanium dioxide (TiO_2). The new procedure exploits TiO_2's ability to deactivate the cancer drug so that only the tumour is attacked and the sometimes debilitating side effects are diminished. The cancer drug is delivered on nanograins of polymer-coated TiO_2 that are small enough to be taken up by cells. The healthy tissue surrounding the tumour is then exposed to ultraviolet light that activates the TiO_2 and degrades the surplus cancer drug. Another nanoparticle technology uses magnetic ferrofluids comprising superparamagnetic Fe_2O_3 particles for targeted drug delivery.[30]

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[29] Holt, G.C. The take-up of near-patient testing (lab-on-a-chip) . *Nanotechnol. Perceptions* **13** (2017) 45–54.

[30] Kurasbediani, M. et al. Targeted delivery of quercetin-loaded magnetic nanoparticles inhibits kainate-induced epileptiform discharges. *J. Biol. Phys. Chem.* **20** (2020) 27–31.

6. Summary and conclusions

The circular industrial economy is an opportunity for disruptive change towards a resilient and sustainable society, which balances economic, ecologic and social objectives in a long-term stewardship of preserving the quality and quantities of stocks. Its attitude of caring for existing stock values can be compared to managing water in a lake. This needs a very different attitude from managing the water flow in a river, which is constantly renewed and the volume of which constantly changes.

6.1 Shifts in the values and processes of the circular economy affect M3 industries

Because every loss of material is a reduction of wealth in the circular economy, it emphasizes resilience, risk management and loss prevention. In the linear economy, by contrast, losses increase production flows and growth (in GDP) and may not hurt those directly and immediately affected, being paid for by insurance companies.

The circular industrial economy is focused on optimizing the use phase of objects and materials and is driven by economics, innovation and competitiveness; the social and environmental benefits come as a free gift or collaterally. The economic actors in control of the circular economy are the owner–users of objects; ownership and liability are central.

Caveat: a circular industrial economy of maintaining values of manufactured stocks is especially appropriate for regions where people have overcome a circular economy of poverty and scarcity, where Maslow's basic needs for shelter, food, security and infrastructure are largely fulfilled.

Today's activity of the materials, minerals and mining (M3) sector—transforming natural resources into base materials at the site of the resources, and selling them to manufacturing industries—puts it at the pole position of the "river" or linear industrial economy. This pole position incurs a major backlash when material flows through the economy slow down—the M3 sectors are the last to know; proactive strategies are thus vital. Such a slowdown can be caused by a number of events; each single one will reduce the industrial demand for resources:

- technology changes causing demand slow-downs are:
  - long-life technologies, such as electric motors with a technical life thrice that of combustion engines;
  - market introduction of easily and fully delinkable molecules, reusing which will replace virgin resources;
  - nanotechnologies improving the efficiency or performance of materials in use;
- commercial innovation inducing slow-downs due to manufacturers or fleet managers changing their business models to selling objects as a service and fully exploiting their service-lives through repair, cascading reuse and remanufacture;
- user behaviour-linked slow-downs due to a(n):
  - longer service-life of objects and materials through easier reuse and repair options;
  - shift from fashion to function;
  - more efficient use of objects and materials through, for example, sharing strategies;
  - attitude of waste prevention, passing used objects to others instead of disposal;
- ownership-linked shortcuts to avoid compliance costs:

  - commodity traders switching from flow to stock management;
  - fleet managers recovering their atoms and molecules from used objects for their own reuse;
  - nation-states adopting a licence-to-mine policy for natural resources.

By being the first to act, M3 companies can stay in the driving seat and prevent revenue losses by shifting from flow to stock dependence. The circular industrial economy enables them to achieve this by:

- exploiting opportunities at the end of the service-life of objects, by recovering base materials for reprocessing and resale;
- developing rent-a-molecule strategies for selling the use of base materials while maintaining ownership of molecules, and harvesting revenue from the stocks in use in the market not from the flows at the point of sale.

Both options involve structural changes—a descaling and decentralization of M3 activities. The latter has been a general economic trend for some time. Both options will reduce the environmental and social detriments of mining and thus improve the corporate social responsibility rating of M3 companies as well as reducing their revenue volatility.

6.2 A shift of emphasis from the material to the immaterial world

On a global level, the corporate liability for compliance with international regulations around the UN's sustainable development goals (SDGs), such as proof of absence of child labour and conflict minerals, could shift from the mine to the corporate HQ, ultimately transforming traders into fleet managers of atoms and molecules to control risks.[31] On a national level, external framework conditions are a lever for change:

- laws imposing an internalization of external costs (through carbon and waste taxes, the full producer liability) will influence corporate strategies;
- redefining waste as wasted resources, as derelict objects with no positive economic value and no liable owner, will capacitate policies of restricting the linear economy, for instance through deposit laws and full producer liability;
- sustainable taxation, such as taxing resource consumption instead of wage labour, will change the balance between resource and labour costs. As a result, reusable goods, components and materials will become the preferred options of many producers and investors for economic and risk management reasons.

On an object level,

- some EU member states' courts have started to accept use value as an alternative to depreciated value in third party liability insurance. A generalization of this circular economy principle will create better and more diversified second-hand markets for durable objects;
- producer liability for performance in use, which began decades ago, hitting especially the tobacco and asbestos industries, is now spreading to complex systems such as cars (diesel engines) and aircraft (Boeing 737 MAX).

On a supervisory level, stock administration has become a hot topic in politics with a view of identifying decentralized resource stocks for later urban mining options:

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[31] The Responsible Business Initiative (*Konzernverantwortungsinitiative*), on which the Swiss people will vote on 29 November 2020.

- information systems recording the environmental performance of the raw materials and components embodied in products;
- data management tools to monitor raw material use in manufacturing at the beginning of the pipe and recovery at the end of the pipe.

6.3 Broadening bioeconomy options

Circularity is the principle ruling nature: the circularity of water, minerals, plants and animals is as old as the planet. People have always used natural materials in an enforced circular society of poverty and scarcity based on good husbandry: *use it up, wear it out, make it do or do without,* well into the era of the Industrial Revolution.

Synthetic man-made materials appeared only with the Anthropocene. They are unknown to nature and outside its circularity, and thus introduce a human liability, which was ignored for a long time by society (analysed in §2).

The EU defines "bioeconomy" as those parts of the economy that use renewable biological resources from land and sea—such as crops, forests, fish, animals and microorganisms—to produce food, materials and energy.[32] On 20 July 2018, the European Commission launched the new Bioeconomy Knowledge Centre to better support EU and national policymakers and stakeholders with science-based evidence in this field. The platform does not primarily generate knowledge but collects, structures and makes accessible knowledge from a wide range of scientific disciplines and sources, especially concerning the sustainable production of renewable biological resources and their conversion into valuable products.[33]

Yet a modern bioeconomy that has gone beyond stone, wood and leather goes much further and blurs the frontiers between nature, man-made materials and digital data. It encompasses such "manufactured nature" as:

- Biochemistry, biosimilars, architectured molecules, molecular machines, diagnostics, pharmacogenomics and pharmacogenetics, and raises ethical issues concerning people and stem cells, CRISPR etc.;
- Bioenergy, such as nuclear medicine, magnetic resonance imaging (MRI) and solar hydrogen;
- BIG DATA created by and harvested from individual users.

6.4 The circular industrial economy and the immaterial economy

The mechanical and later electromechanical goods of the linear industrial economy had a single identity, ownership and liability, which passed from seller to buyer at every point of sale and included the right to repair. Goods incorporating electronics introduced a "split personality" of hardware and software with separate and conflicting control and fault potentials. Stanley Kubrick's movie *2001: A Space Odyssey*[34] demonstrated that in any showdown, hardware under user control remained in the driving seat.

In so-called less developed countries, this dominance of hardware enables economic actors in control to exploit the era of R strategies of extending the service life of objects, if necessary

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[32] https://ec.europa.eu/research/bioeconomy/index.cfm

[33] https://ec.europa.eu/research/bioeconomy/index.cfm?pg=policy&lib=observatory

[34] Based on the eponymous novel by Arthur C. Clarke.

by ripping out defective electronic parts and replacing them with (electro)mechanical alternatives. However, the era of interconnected technical systems and the Internet of Things (IoT) has overturned this rule. Objects have now lives of their own, their masters are no longer the owner-users but the software manufacturers or IoT supervisors who exercise control without having ownership, liability or accountability, such as smartphone producers or salespeople. This confusion is specific to the linear industrial economy of selling objects. It disappears in the performance economy selling performance or the use of objects and molecules, because physical ownership, control and liability for performance in use remain in one hand. The user is protected by the "no use, no pay" principle.

Data mining in the digital economy—BIG DATA—has become a major new industrial activity. It is built on nanotechnologies and despite its immaterial character (data "clouds") uses numerous objects such as smartphones and a huge physical infrastructure of server farms, satellites and communications systems often owned by the data traders. As with synthetic materials, society—politicians—have underestimated the issues involved in the exploitation of this new resource. IoT and the digital economy blur the topics of ownership, authorship, control and liability. The Performance Economy concentrates these issues in one liable economic actor (Fig. 6).

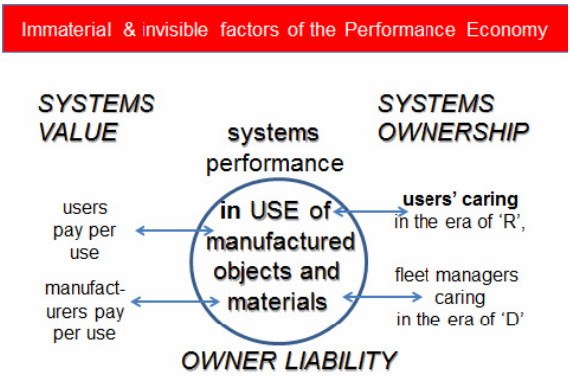

Figure 6. The Performance Economy unifies value, ownership and liability in one hand.

The topic of the junction of the circular economy and intelligent decentralization, nanotechnologies and materials, minerals and mining comprises a wealth of innovation in a jungle of ownership, liability and performance issues. This paper has tried to highlight some of the opportunities involved.