Resourcing the future

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Universiteit Leiden

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Resourcing the future

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Mevrouw de rector magnificus, geacht faculteitsbestuur, zeer gewaardeerde toehoorders.

Resourcing the past
"Resourcing the Future", that is the topic of my lecture. All societies, present and past, have a material basis, a physical foundation in the form of materials that are used for food, energy, shelter, tools, and products.[1] Theodore Roosevelt once said "The more you know about the past, the better prepared you are for the future", so let's follow his advice and take a step back first.

Stone Age hunters and gatherers relied on the materials readily available to them, such as water, fruits, wildlife, wood, and rocks. With the advent of the agricultural revolution, humans acquired the knowledge to cultivate crops and raise animals. Next to sunlight for growing crops, wood remained the primary source of energy and, in conjunction with rocks and clay, served as the building blocks for shelters, tools, and various other products.

Early use of metals
Practically all technology we use today would be impossible without the utilization of a particular group of materials: metals.

While metals have likely been utilized by humans for as long as they've inhabited the Earth, their usage was initially confined to those metals found in their pure metallic state in nature. These primarily consisted of gold, copper, and rare meteoric iron, possibly employed in crafting the iron dagger that was found in Tutankhamun's mummy. As these metals were very rare and distinctly different from any other naturally occurring materials, they held immense value and were predominantly employed for ornamental purposes.

It was only after the development of technology enabling the extraction of metals from their ores that metals began to exert a substantial impact on human societies. Metals became pivotal for crafting tools and weapons that far surpassed their stone and wood counterparts, as metal is less brittle and can be easily molded into desired shapes. One could argue that, following the agricultural revolution, the widespread integration of metals marked the second major transformation in the material foundation of human societies.

Interestingly, the use of metals also brought the possibility of creating a truly circular economy into focus. Wooden and stone tools and weapons were rendered useless once they broke, except maybe for some downcycling. In contrast, metal items could be conveniently melted down and recycled. I will delve deeper into this distinctive property of metals later in this lecture.

Copper's initial production likely occurred unintentionally in pottery furnaces, which provided the necessary heat as well as charcoal that served as a reduction agent. Shortly after the advancement of copper production technology, other metals such as silver, tin, lead, and zinc were also extracted from their respective ores using comparable techniques. Combining copper with tin yielded a material far more practical than pure copper: bronze.

How the Bronze Age cultivated continental supply chains and their collapse with the emergence of the Iron Age
The Bronze Age underscores an intriguing aspect of employing more intricate materials and products—the necessity for more complex supply chains. Since copper and tin ores are rarely found in proximity, civilizations became reliant on foreign resources and the long-distance transportation of raw materials.[2]

The Bronze Age came to an end during the Late Bronze Age Collapse in the 12th century BC. While numerous factors have been proposed as potential causes for this collapse, one significant factor was the transition in society's material foundation, shifting from bronze to iron. This shift disrupted the established distribution of power across Eurasia

Iron is much stronger and tougher than bronze, but it is much harder to extract from its ore than copper and tin. The technology to produce iron from iron ore was probably developed around 1300 – 1100 BC. Iron could be produced using only iron ore and charcoal derived from wood. As both forests and iron ore were abundant and widespread throughout ancient Europe and the Middle East, the need for intricate trade networks diminished. Consequently, the Bronze Age trade networks collapsed concurrently with the Bronze Age itself. This serves as a compelling example of how changes in the material basis can reshape societies and the relationships between different societies.

While the production of iron, and more significantly, steel—an alloy of iron and carbon known for its superior strength and toughness—underwent numerous technological advancements, the material foundation of the most modern societies remained relatively unchanged until the mid-18th century.

Metal smelting and deforestation

In their 2010 book, 'Linkages of Sustainability,' Tom Graedel from Yale University, and nestor of the field of Industrial Ecology and my CML colleague, Ester van der Voet, explore numerous interconnections between different resources within our current global economy. The production of metals offers an early and illustrative example of such linkages.[3]

The process of smelting metal ores necessitates the use of heat and a reducing agent. Prior to 1750, the sole available reducing agent was charcoal derived from wood. Consequently, regions engaged in metal smelting experienced a substantial and increasing demand for fuelwood and charcoal, leading to extensive deforestation in many areas as described by John Perlin by his book about the importance of wood for the development of civilization[4]. Cyprus, for instance, underwent deforestation on two occasions due to copper smelting: first during the Late Bronze Age between 1500-1200 BC and later during the Roman Annexation, commencing in 50 BC.

Some 17 centuries later, iron smelting led to extensive deforestation in England, causing a scarcity of wood for shipbuilding and heating. The shortage of fuelwood eventually led to the adoption of coal as a heating fuel in the late 16th century, despite the "foul fumes" it emitted. Josiah Tucker, an economist of that era, attributed the wood scarcity to "the increasing population and the rapid progress made by the island's inhabitants in arts, sciences, trades, and manufacturing." Does this sound familiar? [4]

The link between wood and metal production thus not only provides a clear example of how resources can be interlinked, but it also shows how these interlinkages can cause competition amongst several applications as well as significant environmental issues like deforestation, local air pollution and (the start of) climate change.

Unprocessed coal couldn't effectively replace charcoal in iron production because of its impurities. Only in the 1740s, after the optimization of the process for deriving coke from coal, could coal serve as a substitute for charcoal. This development bolstered both iron production and the utilization of coal. Subsequently, it paved the way for the creation of the first steam engines, marking the inception of what we now refer to as the Industrial Revolution.

The Industrial Revolution: a fundamental change in material basis of society

The industrial revolution is often seen as an energy transition, but I would argue it was in fact a transition of the material basis of society, thus a materials transition, from wood as the main source of energy to coal. The use of coal combined with increased production of steel led to large scale industrialization of societies. It also revolutionized long distance transport with the introduction of the railways and steam ships, the first ships that were not depended on the winds to travel the globe. This in turn made transport much cheaper and faster and made global trade of relatively low-value commodities profitable.

By the end of the 19th century, the advent of the internal combustion engine introduced a practical application for another previously underutilized fossil fuel: crude oil. This innovation transformed transportation by enabling private and individual mobility through the introduction of automobiles. Furthermore, natural gas emerged as a valuable and relatively clean energy source for both industrial applications and electricity generation.

Fast forward to 1990, fossil fuels account for over 75% of the total global primary energy supply, while solar and wind combined constituted less than 1%. The global economy was thriving and enjoying the benefits of increased globalization. However, in stark contrast, the global ecology was grappling with extensive biodiversity loss and the early indications of severe consequences resulting from human-induced climate change. It became evident to many at that time that a shift away from fossil fuels back to renewable sources was imperative. This transition is, again, not merely an energy shift but also a transition in materials: from fossil fuels to the metals and other materials required to harness and concentrate the diffuse energy from sunlight and wind.

Despite the remarkable growth of wind and solar power in the past two decades, we are still in the nascent stages of this transition, but the contribution of solar and wind power is on the verge of becoming 'material'[5]. To achieve the IPCC climate goals for 2050, we have a considerable journey ahead, and the transition must accelerate even further.[6] This entails a scale-up in mining and refining of metals that at an unprecedented rate and scale to provide the materials required for the wind turbines, solar cells, and electric vehicles essential for a complete transition.

From fuels to metals: the ongoing transition
So, humanity has undergone several transitions in its material basis in the past. Each time, these transitions resulted in profound technological and societal shifts as well as changes in the dynamics between different societies. This time will be no exception, with the notable difference being the immense scale of the transition. This scale is driven by our larger global population, a significantly expanded economy, and because of that, the substantially greater quantities of energy and materials we consume compared to previous transitions.

Furthermore, due to globalization, our production and consumption systems form complex networks that span the globe. Our ongoing efforts to combat climate change will have far-reaching implications for the global economy. Industries like oil refining and coal mining will dwindle, while wind turbine and solar cell manufacturing will thrive. Electric vehicles will reduce the need for traditional car maintenance, but maintenance for wind turbines and solar parks will rise. Countries that heavily rely on fossil fuel exports will need to diversify their sources of income, while nations endowed with abundant solar, wind, and metal resources stand to benefit from these assets. In other words, there will be winners and losers, and the global balance of power could undergo significant shifts.

From securing a continuous inflow of fossil fuels to the fostering of a stock of metals in society
The transition from fossil fuels to metals signifies a shift in our focus, moving from securing a continuous inflow of fossil fuels to fostering a stock of metals within our society. Consequently, the energy transition is not merely a material shift but also a transition from a linear to a circular economy.

When fossil fuels are burned for energy production, they are irretrievably lost in the process. Therefore, an energy system reliant on fossil fuels must ensure a continuous influx of these materials. This has been a primary focus of modern economies for the past two centuries. Crude oil resources are less evenly distributed globally than coal, and as oil supplanted coal as the primary energy source, it had significant geopolitical implications, leading to numerous wars fought for control.

In contrast, the situation for metals used in wind turbines, solar cells, and electric vehicles is entirely different. These metals are not lost during use; they can be reclaimed, reused, and recycled. Research conducted in collaboration with Coen van der Giesen, Ester van der Voet and Gert Jan Kramer has demonstrated that electricity generated from renewables is far more metal-intensive than fossil fuel-based electricity[7]. This is because fossil fuels are highly energy-dense, while sunlight and wind represent diffuse energy sources, necessitating large surface areas for capturing significant amounts of this energy.

Electric vehicles also exhibit a considerably higher material demand than gasoline and diesel cars because they must replace a 20 kg fuel tank with a battery containing several hundred kilograms of metals, including lithium, nickel, cobalt, manganese and copper, as evidenced by the work of my PhD student, Yanan Liang[8]. Consequently, the energy transition will necessitate the accumulation of a substantial stock of metals in electric vehicles, solar cells, wind turbines, the electricity grid, hydrogen production and storage facilities, and numerous other technologies.

An important question we should pose to ourselves is whether we truly require these materials in the first place. For instance, a decrease in energy demand leads to a reduced need for metals. Additionally, we must consider whether it makes sense to merely replace gasoline cars with electric cars having the same range. Should we instead concentrate on fast charging and shorter range electric vehicles, or perhaps promote a modal shift towards public transportation and e-bikes? Both alternatives have the potential to significantly decrease the demand for metals. Moreover, shifts in technology can also have a profound impact on reducing metal demand. Presently, there are two primary competing battery technologies: NMC (Nickel Manganese Cobalt) and LFP (Lithium Iron Phosphate). LFP, by virtue of not requiring nickel, manganese, or cobalt, has the potential to drastically diminish the demand for these scarce metals. Therefore, the strategies of demand reduction and substitution should always be the initial considerations.

For the in-use stocks, our focus can shift towards nurturing and maximizing its utility. However, our ability to reuse and recycle products and the embedded materials therein depends heavily on how we design them. This underscores the significance of the work undertaken by colleagues Conny Bakker, Ruud Balkenende, and Benjamin Sprecher from the Department of Industrial Design Engineering at Delft University of Technology. In collaboration with them and colleague Arjan de Koning and Remy Elzinga from Utrecht University and commissioned by PBL (Netherlands Environmental Assessment Agency), we are presently investigating how renewable energy technologies can be rendered more circular through innovations in their design and the design of the systems in which they operate[9]. In addition to recycling options, this includes considerations related to substitution, re-design, and waste reduction.

Within our research at CML on metal recycling, we have concentrated on rare earth magnets containing elements such as neodymium and dysprosium. Benjamin Sprecher successfully completed his PhD on these rare earth elements in 2016[10], and our current PhD students, Sander van Nielen, Brenda Xicotentcatl, and Maarten Koese, are actively engaged in two European projects: SUSMAGPRO[11] and REESILIENCE[12]. These projects are focused on the recycling and reuse of rare earth permanent magnets, which hold significance for both electric vehicle motors and wind turbine generators.

Through these initiatives, we aim to demonstrate that, despite the absence of operational rare earth mines in the EU, there exists substantial potential to reduce import dependency by tapping into the so-called "Urban Mine" that consists of all materials in societal stocks that can potentially be re-used and recycled. Indeed, for many of the materials used in batteries, solar cells, wind turbines, and the electricity grid, the urban mining approach could potentially fulfill most of the EU's needs by 2050 and beyond.

Responsible Sourcing

As we need more metal mining in the future, we also need to consider the environmental and social impacts of these mines. Europe is highly dependent on imports of critical and strategic materials. Many of these materials are mined in developing countries in South America, Africa and Asia. In her work on responsible sourcing in the European CERA project[13], PhD student Susan van den Brink analyzed how the concept of responsible sourcing can be defined. She also mapped the supply chain of cobalt, a key ingredient in today's batteries. The aim of the CERA project was to develop a certification scheme for responsible mining. Independently verified certification appears to be a simple way to ensure that certain social and environmental standards are met. Mining companies that want to be certified must comply with the standards and may receive a price premium for the certified materials they produce. Problem solved it would seem. However, the example of cobalt shows that this is not as simple as it seems. Around 15-20% of cobalt comes from artisanal mining, small mines run by small communities or even families. This type of mining is often associated with things like child labor, forced labor, problematic working conditions and environmental mismanagement. At the same time, we know that around 200 million people depend on artisanal and small-scale mining for their livelihoods. Our interactions with Leiden anthropologists Sabine Luning and Esther van der Camp have been very helpful in understanding the dilemmas when discussing artisanal mining. Artisanal miners cannot be held to the same standards as large-scale mining companies. A different approach is needed for them, one that focuses on progress rather than compliance with set standards.
This work is now being continued in the MADITRACE project, in which colleagues Sónia Cunha, Robert Istrate and Glenn Aguilar are mapping the supply chains of metals critical to the energy transition and conducting life cycle assessments to support certification of both primary and secondary mining and refining of metals.[14]

The energy transition will require less mining, not more

We have addressed the required upscaling of metal mining that is required for the energy transition. This is often referred to in public discourse as the "dirty secret" of the energy transition. It is obvious that additional metal mining will have additional environmental and social impacts. What is often overlooked however is that the energy transition will lead to less mining, not more. This is because we will need much less coal, oil and natural gas. In a paper based on the work of master student Joey Nijnens that will soon be published, we show that less material needs to be mined and that in the long run total mining can be reduced significantly compared to current levels.

From Globalization to strategic autonomy

Globalization of and complexity of supply chains is not limited to the energy system. The supply chains for common everyday products like cars, washing machines, TVs, mobile phones, and laptops have become remarkably complex in terms of material composition. It is entirely possible for a washing machine manufactured in Europe to contain steel produced in China, derived from iron ore sourced from Australia. Similarly, the same washing machine could include plastics made in Germany from oil from Saudi Arabia, electric motors with copper from Chilean mines, and magnets made in China from rare earths ores obtained from Myanmar. This highlights the presence of a complex and global network of supply chains behind most of the products we all use in our daily lives.

Globalization offers significant advantages for the global economy. Theoretically, it encourages regional specialization, resulting in production taking place in locations with optimal conditions, thus maintaining low prices for products and services. However, the corona crisis and the Russian invasion of Ukraine exposed a significant drawback of globalization: the loss of autonomy. Throughout the corona crisis, it became evident that Europe and the U.S. relied heavily on China to produce relatively simple but essential products like facemasks, protective clothing, and medical consumables. Additionally, the invasion of Ukraine by Russia emphasized Europe's dependency on Russian gas for energy supplies. Even though Europe is transitioning away from fossil fuels, this process takes time, and the abrupt disruption of gas supplies could only barely be absorbed and lead to a permanent increase in energy prices in Europe.[15]

These examples, brought to light by chance through unforeseen events, are just the tip of the iceberg. Dependency issues like these are present in many other supply chains. Over the past decades, the focus on globalization aimed at reducing costs, but it has sometimes compromised resilience and autonomy. The level of resilience indicates the capacity to absorb internal and external disruptions. To enhance resilience in supply chains, flexibility can be fostered by diversifying suppliers and developing alternatives for raw materials, production routes, or product design. Moreover, strategic stockpiles of essential raw materials, semi-finished products, and components can buy valuable time in the face of acute challenges. Especially when it comes to strategic sectors like energy, defense and ICT governments aim for what in the EU is labelled "Strategic Autonomy"[16] [17].

Resilience and strategic autonomy come at a cost

Achieving resilience and strategic autonomy requires effort and investment. Accumulating reserves, incorporating safeguards, diversifying suppliers, selecting alternative materials or product designs—these strategies enhance autonomy and resilience but entail additional expenses.

From globalization to protectionism

The past few years have been characterized by a strong increase in protectionist measures within the major economic power blocs. In the US, the Inflation Reduction Act (IRA) was introduced with the aim of providing a boost to the American industry. Particularly, industries deemed strategically important receive support under this act. These include sectors like ICT, defense, renewable energy, electric vehicles, and batteries. Essentially, products manufactured in the US using raw materials extracted and/or refined within the US are eligible for significant subsidies from the US government[18].

In March of this year, the European Commission launched two legislative proposals that align with the US policies: the 'Critical Raw Materials Act' (CRMA)[19] and the 'Net Zero Industry Act'[20]. The Critical Raw Materials Act suggests measures to reduce the dependence on imported Critical Raw Materials. The idea is to stimulate mining and refining within the Union, promote imports from friendly countries, and limit over-reliance on a single supplier. The Net Zero Industries Act aims to scale up the manufacturing of clean technologies in the EU, thereby making it less dependent on imported products and technologies.

The policies in the US and EU partially respond to China's dominant role in the supply chains of crucial and strategic materials, semi-products, and technology. In 2015 China introduced its "Made in China 2025" policy to further develop the manufacturing sector of China[21]. This helped China to become the world's largest producer of batteries for electric vehicles, solar cells, wind turbine magnets, and the required raw materials for manufacturing these products. Many Chinese companies have close ties to the government, which means that China's strategic interests are often pursued by these companies.

Overall, there is a movement away from further globalization towards a more protectionist geopolitics. However, this does not signify the end of globalization as some have tried to argue but rather a reconsideration of strategic dependencies. In fact, when these measures aim to favor technologies and processes with lower environmental and social impacts, they could potentially accelerate the transition to a more sustainable society.

Critical Raw Materials

Some materials are more equal than others. In a world where strategic autonomy is growing in significance, ensuring a secure supply of raw materials has risen in the hierarchy of political priorities. The term 'Critical Raw Materials' is now frequently employed within policy contexts to sharpen the focus on materials critical to the economy and potentially vulnerable in terms of supply.

To qualify as critical, a material must surpass a certain threshold in both aspects. Different countries and regions employ similar approaches but employ distinct calculation methods for these factors, along with varying thresholds. The work conducted by the International Roundtable on Materials Criticality[22], of which I am an active member, illustrates this diversity[23].

A common thread among these methods is the concentration on mining locations when assessing supply risk. If many mines are spread worldwide, and mining activities occur in politically stable regions, the supply risk is considered low, and vice versa. However, supply risks aren't limited to mining; they can also manifest in subsequent stages of the supply chain, such as refining, distribution, and the production of semi-products and final goods.

For instance, Africa is increasingly vital as a supplier of raw materials, including several critical ones. Nevertheless, the continent's infrastructure is notably deficient, with most exports channeled through just a few viable ports. In addition to the physical vulnerabilities, there are also noteworthy political and social factors that could precipitate supply disruptions. Lately, we have witnessed a series of coups that have the potential to destabilize African countries that export raw materials.

From Critical Raw Materials to resilient supply chains

All of this underscores the need to broaden our focus beyond individual raw materials if we genuinely wish to avert potential supply vulnerabilities. The term "resilient supply chains" has been entrenched in logistics for over four decades. Drawing from the research of Benjamin Sprecher, we introduced this concept into the realm of Critical Raw Materials[10]. Through a system dynamics approach, and in collaboration with Delft colleague Willem Auping, who was pursuing similar research, this concept has evolved further and is now undergoing in-depth quantitative case studies performed by PhD student Jessie Bradley.

One of the central messages stemming from this body of work is that criticality is less a characteristic of an individual material and more a characteristic of the entire supply chain. Therefore, the pursuit of strategic autonomy should primarily focus on fostering resilient supply chains. Furthermore, it's essential to recognize that strategic autonomy does not equate to complete self-sufficiency but entails the development of resilient supply chains encompassing critical materials, technologies, semi-products, and final products.

Resourcing the future

Now let's come back to the title of this lecture: resourcing the future. It is hard if not impossible to envision a future in which humanity is entirely detached from any form of material dependency. So, what would a sustainable societal metabolism resemble? First, let's examine the types of raw materials that can be employed[24].

In a sustainable metabolism, most of the energy should not be derived from materials such as biomass, fossil fuels, or uranium. Instead, in a sustainable energy system, the primary source of energy should be sunlight and its derivative, wind. We may still utilize hydropower and geothermal energy where they are viable, as well as some biomass energy derived from waste flows when no alternative uses for this material exists. Perhaps nuclear fusion could become an exception to this rule, but let's just say I won't hold my breath.

The production of all other organic chemicals and materials must be based either on biomass or synthetic precursors derived from atmospheric CO_2 and hydrogen generated through renewable energy sources. Food, undoubtedly the most critical component within this category, will primarily rely on agriculture, with lab-grown meat potentially replacing traditional livestock and fisheries. The nutrients required for crop growth should be produced using renewable energy and be recycled as much as possible.

Natural fibers will largely continue to be sourced from agriculture, although they can be substituted with synthetic fibers. Products crafted from these fibers, primarily clothing, should adhere to the principles of a circular economy, promoting reduced consumption, sustainable use, reuse, and recycling.

Construction materials should primarily rely on locally abundant minerals and resources. Materials such as stone, clay, sand, and wood will all be incorporated into construction, with the specific mix determined by their availability in the local area. The production and utilization of buildings and infrastructure should again adhere to the principles of the circular economy.

Now, let's turn our attention to my favorite group of materials, you may have guessed it by now: metals! Just like fibers and construction materials, in a sustainable metal metabolism, metals should be utilized in line with the principles of the Circular Economy. Metals, however, possess a distinct advantage: in theory, they can be recycled indefinitely without any loss in quality. In practice, achieving this is much more challenging due to the potential for contamination from the mixing of different metals and alloying elements, which can hinder the achievement of true circularity. The work of Markus holds paramount importance in this regard and should be a must-read for anyone interested in the complexities of metal recycling.

Additionally, some metals are relatively scarce on planet Earth, and their utilization should be minimized whenever possible. There have even been arguments suggesting that we might eventually enter a new Iron Age[25], wherein we would exclusively rely on the most abundant metals[26 27 28]. However, geology and mining experts often adopt a more optimistic outlook regarding the long-term availability of mineral resources[29].

While it's undeniable that the quantity of copper atoms in the Earth's crust is finite, it's also evident that there's a considerable amount of copper that can be extracted beyond our current estimates for economically viable reserves. I'd like to share one of my favorite quotes from a policy document in this context:

"*The threat of the Materials Problem is not that we will suddenly wake up to find the last barrel of oil exhausted or the last ton of lead gone, and that economic activity has suddenly collapsed. The real problem and deeply serious threat is that we shall have to devote constantly increasing efforts to acquire each pound of materials from natural resources which are dwindling both in quality and quantity; thus finding ourselves running faster and faster in order to stay standing still.*"

This quote could easily fit into any policy document addressing this issue over the past two decades, but it is, in fact, extracted from the final report of The President's Materials Policy Commission, also known as The Paley Commission, and was published back in 1952[30].

This quote holds significance because it underscores that the depletion of mineral resources will be a gradual process, and the limiting factor isn't solely the amount of copper in the Earth's crust. Instead, it's constrained by the resources of energy, water, and financial investment we are willing to allocate, as well as the environmental impacts we are willing to tolerate. The fact that this quote dates back to 1952 highlights that the security of material supply has been a recurring topic of discussion and will continue to be so. The abundant availability of affordable raw materials, which form the foundation of our society, is not a given, making it an issue that demands our sustained attention.

A sustainable societal metabolism

In a sustainable societal metabolism, it is imperative that we utilize resources only when necessary, minimize dissipative losses[31], design products for durability, repairability, and reusability, and ensure they are conducive to recycling.

Our goal should be to nurture the ever-expanding stock of materials within society, enhancing our understanding of these materials within the stock by gathering information on their composition, quantity, quality, location, age, and lifespan, among other factors. At CML, our scientific efforts are centered on modeling the stocks and flows of materials in society. My CML colleague José Mogollón is currently overseeing our involvement in two European projects aimed at assisting with this type of modeling: FUTURAM[32] and CE-RISE[33].

However, despite our best efforts in managing societal stocks, there will still be a need for primary mining in the foreseeable future. While the ongoing energy transition will lead to an overall reduction in mining it will also necessitate a significant increase in metals mining over the next decades. This additional mining must be conducted responsibly, prioritizing the mitigation of environmental and social impacts.

To gain insights into the potential impacts of mining on biodiversity, scenarios of future material requirements are increasingly integrated with Geographical Information Systems that incorporate current and anticipated mining operations, environmental data, and biodiversity-related information. Diversification of supply and a focus on local mining, refining, and processing can contribute to greater supply security in Europe. In collaboration with our colleagues from TU-Delft, we are now developing models to better understand the dynamics of supply chains, identifying vulnerabilities, and exploring the consequences of various potential disruptions. This research will help us define what resilient supply chains should encompass.

Closing remarks

Scientific research is a peculiar blend of ideas and insights that spontaneously emerge at the most unexpected locations and at the oddest of times. It involves solitary and labor-intensive efforts, which I like to refer to as "doing the dishes" when teaching my students. Furthermore, it encompasses engaging discussions with mentors, colleagues, and students.

For me personally, engaging in scientific work necessitates an environment that provides safety, freedom, critical yet constructive reflection, and, perhaps most importantly, ample opportunities for laughter. Fortunately, this is precisely what I have found at CML. When I came to CML, Gjalt Huppes was the nestor of the Industrial Ecology group at CML, a true silverback, always kind, always generous in every possible manner but also always challenging on an academic level.

Ester van der Voet is my long-time 'roommate,' at CML. We may have vastly different personalities, but together, we've formed a formidable team with accomplishments we can rightfully take pride in, the pinnacle being the Leiden-Delft Master program Industrial Ecology.

My office neighbors, Jeroen Guinée, Arjan de Koning, and Lauran van Oers, have been an invaluable source of support.

Having colleagues one can rely on, not just in terms of work but also for friendship is of paramount importance. Special thanks go to Paul de Hoog and Jan Boersema for ensuring that there's always a controversial topic up for discussion during CML's famous coffee breaks.

CML has undergone a significant transformation over the years, and I must say, it is even better now. In the past decade, under the leadership of Arnold Tukker, CML has attracted exceptional talent from across the globe, and the institute is flourishing. The list of remarkable individuals is too extensive to detail here, but you know who you are and I'd like to express my gratitude to each and every one of you for being awesome !

A university owes its essence to its students. They not only frequently produce remarkable academic output but also bring youth, vitality, inspiration, and a sense of purpose to the academic arena. I have had the privilege of mentoring numerous exceptional students, and if there's one source of pride I hold dear, it's them! I encounter many of our alumni now as professionals in various organizations, actively reshaping the world for the better.

I would also like to extend my gratitude to the Executive Board of Leiden University for establishing this chair and to the Faculty Board for their support in this process. Special recognition is due to Arnold Tukker and Martina Vijver for their trust and leadership.

Lastly, I want to thank my family and friends, without whom I would not be the person I am today. My deepest thanks to Ella and Lina, who ground me and enrich my life immeasurably, and above all, my thanks go to Annelie, the love of my life.

Ik heb gezegd.

Notes

1 Leiden archaeologist Maikel Kuijpers, who is currently a guest at CML, has authored an outstanding series of articles exploring the relationship between humanity and materials, which I highly recommend: (https://www.universiteitleiden.nl/en/staffmembers/maikel-kuijpers/publications#tab-4)

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16 https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)733589

17 It is important to note here that globalization doesn’t necessarily lead to a decline in resilience and autonomy. When supply is well-distributed, disruptions from one route can be offset by other available routes, enhancing supply security even beyond reliance on a single domestic source.

18 https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/

19 https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747898/EPRS_BRI(2023)747898_EN.pdf

20 https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en

21 https://crsreports.congress.gov/product/pdf/IF/IF10964

22 https://irtc.info

23 Schrijvers, Dieuwertje et al. 2020. “A Review of Methods and Data to Determine Raw Material Criticality.” Resources, Conservation and Recycling 155: 104617.

24 I won’t delve into the topic of water here, as it warrants a discussion of its own.

25 In fact, I would argue we still live in the Iron Age since the in terms of volume iron and steel dwarf the use all other metals.
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32 https://futuram.eu
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Prof. dr. René Kleijn

René Kleijn is a Professor of Resilient Resource Supply at Leiden University in the Netherlands. He holds an MSc in Chemistry and earned his PhD in Industrial Ecology, establishing a solid academic foundation for his work. Additionally, he serves as the Scientific Lead of the Circular Industries Hub at the Leiden-Delft-Erasmus Centre for Sustainability.

Kleijn has made significant contributions to the field of Industrial Ecology, playing a pivotal role in shaping it into a recognized scientific discipline. Furthermore, he was one of the co-founders of the Leiden-Delft master's program in Industrial Ecology, which has since become the largest educational program of its kind worldwide.

His research primarily centers on sustainability matters, employing quantitative methods like Life Cycle Assessment and Substance and Material Flow Analysis. Kleijn's expertise extends across various industries, including chemicals, energy, and recycling, where he effectively applies these methodologies to address environmental challenges.

He has actively participated in numerous large consortia as part of EU-funded research projects. In recent years, his research has focused on critical raw materials, resilient supply chains, circularity, and material constraints within the evolving landscape of the energy transition.

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