Material World. A Substantial Story of Our Past and Future

An intriguing reading

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Ed Conway, a British journalist, was shaped in his thinking by the dominance of financial markets and the rise of digitalisation. He likes to name this world as *ethereal world*. Some years ago, he realised eventually that this ethereal world depends on materials. The breakdown of supply chains opened his eyes for this fact. He delved deeper into the subject and wrote the book *Material World. A Substantial Story of Our Past and Future*. Written for a general public, this book raised my interest due to my interests in materials in general and in metals specifically.

Material World

> "The Material World is what undergirds our everyday lives. Without this place your beautifully designed smartphone wouldn't switch on, your brand new electric car would have no battery. The Material World will not provide you with a gorgeous home. But it will ensure your home can actually stand up. It will keep you warm, clean, fed and well, however little heed you may pay it." (p 13)

In his book Conway explores six materials in depth: sand, salt, iron, copper, oil and lithium.

The book is great reading: an author, new to the subject, firmly rooted in the business world is struck by the fact that his world is dependent on materials:

> "Yet the story doesn't seem to accord with the reality, because this stuff clearly matters. For all that we are told we live in an increasingly dematerialised world, where ever more value lies in intangible items – apps and networks and online services – the physical world continues to underpin everything else." (p 6)

> "But pretty much everything from social networks to retail to financial services is wholly reliant upon the physical infrastructure that facilitates it and the energy that powers it. Without concrete, copper and fibre optics there would be no data centres, no electricity, no internet." (pp 6f)

Conway eventually has come to the insight:

> "This book [is] […] a meditation not so much on the market value of substances but our *dependence* upon them." (p 7)

He writes extensively about the functions of the materials he is using as his cases. He argues again and again that without specific materials the world as we know it will no longer function.

The book is great reading: it is fascinating that Conway does not start with that the earth is matter. That he and his fellow humans are not ethereal, even not when they are part of the world of financial and digital services. They are physical beings. He does not use his newly branded concept of Material World as a shortcut for this part of the world we live in. But his overall message is interesting anyway:

we, humankind and all humans, should understand that the world, he characterises as ethereal, is dependent on materials.

This book is very interesting being an example, that the sense for the natural resources was lost or at least sidelined. Conway argues that this is grounded in the belief of economists that there will be a substitute at hand if a shortage of a needed material may happen. Conway was trained in that framing as he elaborates at the beginning of the book.

He makes a first step in discovering the material side of his ethereal world: he derives from his interest in the functioning of the modern type of economy, digital and all that, that we should be aware and understand its dependence on materials. Overall, the book is an interesting example

- for a renewed interest into the material side of human affairs, when the understanding of their fundamental functions had been lost for long and their availability is commonly taken for granted. It is not by accident that the physical shortages in the supply chains were at the start of Conway's renewed interest.
- what difference it makes when you start proper with the use of materials in contrast to a derived, more narrow interest in the subject.

The book is informative to some degree but one has to have in mind, that Conway had a long way to come closer to the subject. However, it is very useful for the understanding of players shaped by the dominating frame of economics when they start to realise that their world is dependent on materials. It is also fascinating to read how Conway is on his way and experience mines all over the world, a Nevada goldmine, iron mines Pilbara in Western Australia and many more.

Physical, material, ethereal

Conway introduces the term *Material World* (written in capital letters) and took it as his main title. I was surprised about his understanding of the Material World: it is just one part of the overall material world, the part on which the ethereal world is dependent on. He is aware of the natural world (pp 87ff). But his specific interest in materials derived from the ethereal world is forming his concept of the Material World. Presenting his cases such as sand and silicon, he states:

> "These leaps of innovation, from the switch itself to the 'integrated circuit', the first of which was etched on to silicon by Robert Noyce at Fairchild Semiconductor in 1959, represented the physical foundation of the computing age. That word, physical, matters here." (p 89)

Knowing that, it would make a difference to start with the Material World as it is and then proceed in the next step to that part of the world, he is specifically interested in. It is not just a riddle that he decided otherwise because that may be a strategy to attract readers. But it is revealing for a deeper understanding of the players, in the business community, media and politics as well.

He uses the term material not in the understanding of matter and substance but as *produced materials*. He is defining his term Material World as world of materials.

This is not just his personal use of terms. It is used accordingly in the still dominating frame of economists, business world and policy makers all over the world. That is due to the *derived interest* in the subject. *Supply chain troubles* bring the insight on the table that all the marvellous new gadgets and needed infrastructures are functioning only because humankind has discovered how to make use

of materials of the earth. Or to put it another way: to discover the periodic table and how to make use of its elements with 80 per cent metals and semimetals.

Conway presents the supply chains of his cases sand/silicon and alike. On the one hand, he attracts reader to the subject which normally do not bother about the physical prerequisites of the modern economy and way of life. On the other hand, his book is an example that the derived interest is hampering to start from scratch: the physical world as it is, the functionalities of elements and their combinations, the use of its substances by humankind and the characteristics of the dominating forms of uses. To state it differently: analysing the very foundation of the world by its basic substances, geological processes, evolution of life and the history of the use of materials, the material world as it is: material.

Sand – silicon, glass, semiconductors and chips

Conway starts with sand as his first case in point, presenting it as "great enigma of the Material World." (p 31) He tells the history of glass:

> "Glass, in other words, was a foundational innovation, a general purpose technology like the wheel or the steam engine or the silicon chip. This magical product was important not just for what it was but for what it enabled us to do – to make further leaps of imagination." (p 37)

He states that glass is "the World's First Manufactured Product" (p 38). This is just one example that Conway sometimes is somewhat easy going in his writing. But that is just a minor side-remark. He writes in detail about the different qualities of silicon-dioxide quarries. At some point he writes about Otto Schott and his experiments to "improve glass, adding elements from the periodic table to a molten mix, one by one, to see what kinds of effects they would elicit." (p 48).

This is a rare case, when Conway is explicit about the use of the periodic table and the functional qualities of its elements. Otherwise, the perspective on the supply chain is dominating with a focus on technologies, corporations and some elements. He stresses time and again, that countries were dependent on the manufacturing of the leading countries and corporations.

Conway tells the history of glass but it is evident that his interest in sand and silicon is mainly due to the fact that "The Internet Is Made of Glass" (p 59) and that the semiconductors and chips are based on silicon. Therefore, he delineates the race for sand and specifically the demand for specific qualities of sand needed for the digital world (and for concrete as well for that matter).

In Chapter 3 he takes the reader on "The Longest Journey" (p 87) from the quartz sand grains and quarries via smelting of silicon, producing pure silicon, then wafers and finally the end products semiconductors, chips and high-end chips. He continues with the story of the race to nano-structures, but he also informs about the fact of the energy-intense stages of production processes. He emphasises that the *invisibility* of the nano-scales is a major reason that the material dependence of semiconductors and chips is not easily understood.

He is illustrating, what he calls the longest journey, the supply chain of a silicon chip with specific sites and companies.

(1) The first stage is Ferroglobe's Serrabal quartz mine in Galicia (Spain), which "is one of the purest quartz deposits to be found anywhere in the world" (p 94).

(2) The quartz is then carried to the Ferroglobe Sabón plant, near the port of A Coruña and smelted into silicon metal.

(3) The next stage is Wacker, Burghausen, where the granulated metal is processed to polysilicon, "the purest substance in the world" (p 99).

(4) Polysilicon is flown to the outskirts of Portland, Oregon, the production site of Sin-Etsu, a Japanese company which is one of the "titans of the Material World" (p 101). This company is one of the world's leading producers of silicon wafers.

(5) For the process of producing wafers crucibles are made "out of a very particular type of quartz, one you can only get in a single place in the world." (p 105) This quartz is mined in Spruce Pine, North Carolina, which was for a long time operated by the Belgian company Sibelco. Conway stresses this monopoly because the global supply chain is today actually dependent on this specific mine.

(6) He introduces as a sideline that some five to ten companies are active to geological prospecting for alternative mines of the same quality. It is evident, that up to this part of the book Conway is still not yet reasoning about finiteness of resources but is anchored in the world of substitution.

> "No high-purity quartz means no Czochralski crucibles, which means no monocrystalline silicon wafers, which means, well, the end of computer chip manufacture as we know it. We would adapt; find a new process or an alternative substance. But it would be a grisly few years." (p 107)

(7) The next stage is the Southern Taiwan Science and Technology Park located in the outskirts of Tainan. For people working in computing "this is the centre of the universe." (107) In the Fab 18 of TSMC the most advanced high-end chips are produced for such corporations as Apple, Tesla, Nvidia and Qualcomm. Only TSMC and Samsung are capable of producing the actual most advanced chips.

It is evident at this stage of the story, that there is not just one linear supply chain but that there are many lines which are prerequisites for the overall process. Conway is introducing at least some major prerequisites.

(8) The Dutch company ASML is the only corporation which actually can deliver the needed machinery for the photolithography at the quality level required for the extreme ultraviolet light.

(9) Pulse lasers are provided by the German company Trumpf.

(10) Zeiss produces a set of special mirrors. In this case Conway is directly naming molybdenum as an element needed. Otherwise, he has only some aggregate and qualitative statements about "chemicals needed" or that average chips are made up of 60 elements.

While a Taiwanese and a Dutch company are obviously essential in the semi-conductor supply chain, "this is only the tip of the iceberg, for there are hundreds of other companies without whom these somewhat more prominent parts of the supply chain would be unable to function." (p 119) He introduces a few names of other companies as examples for providing critical machinery to the fabs. "Remove one or two of these companies and, well: no more computers and smartphones." (p 119)

Conway has eventually discovered that the smart world is dependent on materials. But his thinking is still dominated by the supply chain logic. He is explicit however, that in fact it is not one linear supply chain but a web of many interwoven supply chains.

Conway is not so much interested in the processes of dissipation, recyclability and all that but on the geopolitical issues. This type of reasoning is according to the still dominating public discourse. However, the book of Conway is a starting point to underpin the dependence on materials, all sorts of incredible qualities of substances and very specialised functions needed. It is a starter to understand: digitalisation – as I call it – is dependent not just on energy but materials. Metals and semimetals.

Salt

As a reader, we are now familiar with the dramaturgy of the book. Conway introduces the case of salt starting at an archaeological site called Street House in UK where salt was extracted as early as 3800-3700 BC. Conway narrates the history of the use of salt, its role in trade and power relations. In the sections about China he mentions a debate in 81 BC at a Han imperial Court, which was "one of the most famous early works on governance, the *Yán Tiě Lùn, the Discourse on Salt and Iron*." (p 137) After many more common stories he comes to "Salt at the Heart of the Modern World" (p 150) with the chloralkali process as "one of the most important industrial achievements of the modern age" (p 151) and the Solvay process. He intersects some side remarks about some unpleasant aspects related to plastic and a more general "there is a dark side to technological progress" (p 157).

He takes speed on when he arrives at the story of saltpetre (salt of the stone) as ingredient of gunpowder. He writes at length about the Saltpetre War between Peru, Bolivia and Chile. The breakthrough came when Fritz Haber solved technically to fix nitrogen from the air. In the Haber-Bosch process ammonia could be manufactured:

> "The Haber-Bosch process, as it has become known, is one of the most important scientific and industrial discoveries in history. It has, in the subsequent century, helped us to feed billions of people. One of the greatest triumphs of humankind during the twentieth century was banishing hunger and famine as a widespread issue." (p 173)

The Haber-Bosch process is not just a story about agriculture and food but also a story about explosives for wars as well. In a postscript Conway adds the story of other salts and again the power derived from the control of these substances. Overall, the case of salt is not as convincing as the case of sand in the previous part of the book.

Iron

Iron is stronger, the metal as well as the next case for the Material World in Conway's book:

> "And think for a moment about what metals actually *are*. While concrete and stone are brittle and prone to cracking and shattering, the atomic structure of metals lend itself to a kind of toughness combined with malleability. They can be cast and hammered into shapes and, most essentially of all, into *tools*." (p 197)
>
> "If what defines humans is our ability to collaborate and wield tools then iron and steel are part of what makes us human. And if sand is the fabric for much of the world and salt is the magic ingredient that helps us transform our world, then iron is what enables us to *do* things, whether

> that is going places, building things, making products or, for that matter, killing each other. Iron and steel are the common thread." (p 197)

Conway explains that iron was not the start of metal smelting but that today it is the dominating metal "accounting for roughly 95 per cent of all the metal we produce and use." (p 197) Iron is part of Conway's Material World because it is a substance which touch our lives every day. He explains the spectrum from cast iron via steel to wrought iron due to its carbon content. Steel has typically less than two per cent carbon and some well below one per cent. Steel is a case that a substance (in this case carbon) may be too much or be too little.

Conway mentions shortly some examples of alloys adding manganese, silicon, chromium, nickel, molybdenum and vanadium. He introduces the Bessemer converter and tells the history of steel and iron. Steel matters because it fostered general purpose technologies and became ubiquitous. He is also aware that steel production is responsible for a relevant share of global greenhouse gas emissions. And in a short while, Conway writes again about one of his favourite topics, the *power* of steel and *geopolitics*.

In a dramaturgical turn he is then going back in time to iron, coal and the Industrial Revolution. Conway really gets into gear when he is introducing examples such as Henry Ford's success with his Model T: his success in mass production was a story of steel. Ford investigated various alloys of steel and decided to use vanadium steel. "Without this lighter, stronger alloy, the Model T might never have happened." (p 227)

In his next chapter Conway is taking more time to dig into the geology of iron ores with an eye on Pilbara in Western Australia, one of major global regions. While China is dominating vast domains of metals, the iron reserves of China are not like the ones in the Pilbara region. Conway describes the conflict between the interests of Rio Tinto and safeguarding sacred places of Aboriginal heritage in some length. In taking up the related scandal, he is very critical with Rio Tinto. This is in contrast to his general worldview close to business. It's not just about the lies of senior managers but he is citing the results of an external review into the company's internal culture: "disturbing patterns of racism, sexism, harassment and sexual assault." (p 242)

His paragraphs about the "Scrap Steel Age" (p 244) are surprising: he is envisioning the perspective that at "some point, maybe Jevons's paradox will no longer apply and we really will have enough." (p 245) But this depends, of course, so the argument goes, on the ability to recycle the scrap in qualities needed.

Copper

Part four of Conway's Material World is about copper. This part is again more convincing and worth to be debated compared to his cases sand and salt. In short:

> "Copper is the great, unseen substrate that supports the modern world as we know it." (p 253)

> "In every conventional power station, wind turbine, geothermal plant or hydroelectric dam, copper is key. […] Take this metal away and much of the electrical infrastructure we rely on is gone." (p 257)

He introduces the history of copper and mining and the development of making use of modern physics for the rise of electricity which in turn gave rise to "the real copper age, the one that still matters today" (p 259). He presents one of the "virtuous circles" he likes, the rise of power stations to supply industry electrolyse processes "defying pessimists" (p 263). In this part of his reasoning Conway is firmly rooted in the common 'pessimist – optimist' framing von Daniel Yergin and alike. But readers may just leave that out. The other text is interesting anyway.

Conway is fascinated by his experiences in the monumental Chuquicamata copper mine situated in the Atacama Desert in Northern Chile:

> "More earth has been removed from here than anywhere else in history, making it one of the more unlikely engineering marvels of the modern age." (p 266)

Seeing the magic of the site, he is also explicit about the other part of the story: "The Mine That Ate a Town" (p 269) as well as the severe environmental and health impacts.

The next subsection "The Bet" (pp 274ff) fascinates as well because it demonstrates that Conway is still torn between his understanding of the material side of the matter and the world of prices economists are focused on. He writes at length about a bet of Paul Ehrlich and Julian Simon regarding prices of copper ten years from now. All the common stereotypes are at display about Cornucopians and Malthusians, the misunderstanding of ten years as "in the long run" and alike. Then Conway turns to The *Limits of Growth* of the Club or Rome. What follows is a lesson for the overall development of natural resources in general and metals specifically.

(1) Finite resources. Conway concedes that "there is no getting away from the fact that our planet and its resources are finite." (p 280)

(2) High-grade copper mined first. Conway also understands that the sweet spots will be commonly used first: "Nor is there any escaping the fact that copper is becoming ever trickier to mine." (p 280) The ores in Cornwall contained 12 per cent copper back in the eighteenth century but by late nineteenth century that had dropped below 8 per cent: "Around the world, by the early twentieth century many of the most promising grades had already been mined out." (p 280) The search for methods to make use of lower-grade copper ores was eventually successful:

> "It is a rarely told story: even as Henry Ford was mass producing cars in Detroit, the Guggenheims were quietly turning mining into a mass production activity – or 'mass destruction', as some have called it." (p 281)

The grades of ore fell in the mine of Chuquicamata: "from 2.4 per cent in 1913 to down below 2 per cent by the middle of the century and below 1 per cent by its end." (p 282)

(3) Effort is increasing accordingly. Conway is also aware that this comes at a price: energy needed rose, the amount of water consumed and the quantity of stones to be moved as well.

(4) Inflation-adjusted copper price essentially flat. But Conway stresses the productivity increase and further developments of mining technologies, in this case adding to the biggest global open-pit mine "the biggest underground mined in the world." (p 283) In short:

> "It is a productivity miracle, just as impressive as Moore's law for semiconductors – yet few people, even inside the sector, seem to be all that aware of it." (p 284)

(5) Copper reserves. Technological advances opened the potential to make use of the lower-grade rocks. Conway then focus on the world of "copper reserves left in the world" (p 285). What follows is somewhat funny reasoning. First, Conway rightly explains that reserves are defined what can be economically extracted at a given moment, or in other words the ores in "the kind of time horizon over which miners tend to make plans." (p 286). Then he writes about the *Limits to Growth* stylising it – wrongly – as a report about an imminent catastrophe of a physical supply shortage. And then he tells the dear readers that between 2010 and 2020 207 million tonnes of copper were mined globally, "but far from falling, the total global reserves of copper grew by 240 million tonnes." (p 286)

That's great a message. Reserves are *defined* that with growing quantities of mined metals the reserves will grow. If more copper is mined from large-scale ever-lower grade mines, then the reserves will increase by definition. This is then taken by Conway as an illustration that the supplies have grown. He writes in the next sentences:

> "Ponder that for a moment. Humankind is managing to increase our accessible supplies of this vital material at a rate that comfortably outpaces our actual exploitation of it." (p 286)

(6) Resources. Well, ponder for another moment: Conway knows that the sweet spots with higher grades are mined first. When they are exhausted lower-grade mines have to be mined. Technologies are invented, efforts increased to make use of those mines. If the copper will not be recycled after end-of-life then humankind will have less copper to be used and increasingly more effort is needed. Introduce the energy-metal nexus and the triumphal tone sounds hollow.

Interestingly, Conway knows it. In the following paragraph he is writing that reserve figures are not really valuable but resources are key. Funnily enough, he then writes about the consequences of poorer copper ores and laments that even in the United Nations measures the – increasing – waste rock does not count. And that in a world when carbon emissions have to be decreased and: "All of a sudden copper becomes the backbone of, well, everything." (p 287)

We may be thankful to Conway presenting the strange type of miracle, the wonder world of Friedrich-Wilhelm Wellmer, former president of the German Federal Institute for Geosciences and Natural Resources: the supply of copper will increase with mining ever more copper from ever lower-grade ores. The real fundamental fact is otherwise: *the effort needed is increasing*.

Conway is then, for the first time in his book, introducing recycling as the – desperately – needed good news. Then he is going on:

> "This brings us to the real challenge: not so much that we are likely to run out of the metal, nor that it will become too expensive. The real question is how much more of this blasting and digging people will tolerate." (p 288)

That is a point in case: it is part of the play what is usually termed the social licence to operate and the ecological license to operate, terms not used by Conway himself. But the fundamental task to understand metals proper and the dominating fundamental unsustainable use of metals, not just copper, cannot be argued away.

Conway started his journey into The Material World he has in mind on the insight that the world of finances, digitalisation and all that is dependent on materials, stuff. He is missing the task to

understand the physical world as it is. He sometimes uses the phrase *the world as we know it*. We may add at this point: *the physical world as we may know it and which is useful to try to understand*.

Conway has an add on to his case of copper: deep sea minerals mining and "the mineral treasure lying beneath the water" (p 293). He writes about the International Seabed Authority which is in charge for the common heritage of humankind in the high seas. Conway writes about the state of the art of technologies and the conflicting interests and pressures to start deep sea mining or to block deep sea mining altogether. It is fairly surprising that he argues, that "you could make a case that mining copper, or for that matter cobalt or nickel, from the deep sea is the greenest mining of all." (p 300) Surprising, because he is aware that the knowledge is poor about the vast habitats down there in the deep sea and that "each new study provides more causes for caution" (p 302). But again, he is also very sympathetic with the argument of potential miners.

Finally, Conway is reasoning about the prospects of copper in general and other metals as well because it is needed increasingly for the electrification and to address climate change. Our "ability to squeeze ever more copper out of ever less promising stone" (p 304) will improve and therewith the scrap from the past may become valuable copper.

Oil – the case of fossils

This case is different and not so easily integrated in the story line about the Material World. But Conway tells interestingly for readers not so familiar with it about the super giant field of Ghawar, Saudia Arabia and other parts of the oil story. He writes rightly that fracking started in the 1980s using and combing well-established technologies. This is in contrast to the popular myth of fracking as a game changer due to new technological breakthroughs in the 2000s. He is aware of the ecological impacts of fracking and writes about its geopolitical impacts. He differentiates the various stages of the rise of fossil fuels as the Great Energy Transition, coal, oil and natural gas. He is aware that we interfere with the massive use of fossil deposits into the geological cycles and that we drive climate change.

He writes about the qualities of crude oil and refineries, the technological break-throughs and the geopolitical role of oil in World War II. He is close to be sarcastic when he writes about the story of adding lead to gasoline in order to increase octane levels. He characterises it as "one of the most shameful stories of pollution in modern history" (p 340) because the health and environmental hazards of putting lead in petrol were common knowledge when it started.

Conway writes intensely about the rise of the petrochemical industry which used the by-products of gasoline refineries for their petrochemical products. Readers interested in that part of the story find valuable information such as the six main families of human-made polymers. Conway is aware about the success story of plastics as well the down-sides. I have termed that the *impacts of success* ("Die Folgen des Erfolgs", Held 1988: p 3f).

Conway adds a "Postscript: Peak Oil". He tells the story in lines of peak demand, which is not a surprise because he writes in the frame of Daniel Yergin and alike. What is surprising however, that Conway is very lax when he is using peak oil in an understanding "the end of crude oil" and not as the maximum of oil production. Anyway, the part about oil is not a really convincing case for his Material World.

Lithium

The final part about the case of lithium is far more interesting, not just being another example for a metal but also introducing a case which is on the agenda only very recently. Again, it is a derived interest. This "magical metal" (p 373) is light, conductive and with a high electrochemical power. Conway narrates the development of taming the inherent reactivity of lithium. After many decades and stages of development the effort eventually succeeded in a battery which could be used at scale. The lithium-ion batteries were used in consumer goods and finally became a success story powering smartphones. Lithium is also at the heart of batteries for e-cars.

Conway takes the reader to the Salar de Atacama, Chile and informs about the mining of lithium there. He writes also extensively about the "Darker Side of the Lightest Metal" (p 384).

> "Yet it is also hard to escape a more discomforting thought: are we just replacing one form of environmental footprint with another?" (p 384)

Lithium got its name from the Greek word for stone, *lithos*. It is mined from hard rock lithium ores as well as from the brine of salt lakes. There is a pressure to utilise the lithium depots due to the rising demand in the energy transition and drivetrain transition on the one hand. On the other hand, there are environmental impacts. This is specifically an issue when lithium is mined in one of the driest climates on earth, such as the Atacama Desert in Northern Chile. The inhabitants claim that this is a misuse of water, while the miners frame it as a 'liquid mineral'.

> "As with deep-sea mining, another effort to exploit unfamiliar territory, the unknowns dramatically outnumber the knowns." (p 391)

Conway then writes about the shift in world's geopolitical map due to the rise of lithium as a fundamental metal and the global geological distribution of the rich mineral deposits of lithium in contrast to the geological distribution of crude oil deposits.

Conway marvels about the first gigafactories to the manufacture of batteries. Interestingly, the fame was globally with Tesla but in fact two-thirds of the first of such a factory is owned and managed by Panasonic. This is a good example: while in some other parts of his book Conway is still firmly rooted in common misnomers and narratives, Conway also informs often much better compared to the dominant hypes of the day.

That again, can be experienced by readers when Conway proceeds in his story of lithium. He writes in plain English contrary to the 'no worries, we, humankind will succeed with enough supply due to our ingenuity':

> "There are echoes, too, of the nineteenth century, when European countries colonised their way through much of the world. Seeking rubber here, copper there, not to mention other items like gold and saltpetre. Will these periodic rushes for minerals ever end? Are we constantly fated to keep digging and blasting our way deeper into the earth until nothing is left?" (p 412)

Then Conway turns from lithium to cobalt in his chapter about "Unmanufacturing" (p 413). He explores the legacy of colonialism about the 'scramble for Africa' by European countries. This scramble for resources was particularly brutal, both with minerals and in the form of slavery. Cobalt and the Belgian Congo is one of the examples for the resource curse. Cobalt is typically associated

with copper in ores with grades of cobalt mostly well below 1 per cent. However, in ores in the Democratic Republic of Congo cobalt is part of the mineral mix with grades up to 10 to 15 per cent. This is globally unique. Again, Conway is aware of the fundamental fact of grades of metals, while he tries to convince readers from the contrary in other parts of his book.

Conway tells about the transformation of the Belgian company Union Minière to Umicore of today. This brings Conway finally to urban mining and recycling. He describes it that "we are still a long, long way from that promised land." (p 419) He assumes that in the future most needed material could come from products after end-of-life. In the circular economy waste will be treated as a kind of resource.

> "Recycling goes from being a sideshow to the main show. Everything becomes about closing the loop. […] We will need to work out how to recycle solar panels and wiring and circuitry, and all the other bits and pieces of the Material World." (p 420)

Then, again Conway is somewhat more cautious and writes "in theory one can repurpose it [lithium] without wasting it. In theory." (p 421) Some pages later, readers may learn that Conway knows better, even not "in theory" we can recycle 100 per cent:

> "We are heading, in short, for a bumpy few years. For decades we have convinced ourselves that the main constraint facing humanity is the scope of our imagination. We created an economic system so sophisticated and seamless that it allowed us to forget about the materials upon which it was built. But in attempting to build our way to net zero, we are confronting the inescapable limitations of thermodynamics and material constraints." (p 424)

In short, Conway is torn between his world of business and economics, which shaped him on the one hand and his insights into the material world as it is on the other hand.

He ends this part with his expectations for the way forward: the fossil trio – coal, oil and natural gas – were *burned*. This time might be really different: natural resources will be used "*building* our way into the future." (p 424)

Conclusion

In his conclusion Conway starts with his major messages:

> "Far from being independent from the physical world around us, we have never been more reliant upon it" (p 425).
>
> "As the fruits of the Material World have become cheaper, they have come to account for an ever smaller fraction of our national expenditure, with the result that they are often overlooked in conventional accounts of the economy." (p 428)
>
> "That we do not pay much attention to the Material World is rather the point. Why would we, when it just … works? We have come to expect that gradually, each year, things just get better." (p 429)

I would add: The prerequisite was the discovery of the periodic table of elements in 1869 and the subsequent successful story to learn about the characteristics of the elements and for what functions they can be used. It was about in the 1950s and beginning 1960s that this knowledge

base was available. It was the lifetime achievement of Armin Reller to point out this fundamental fact (Zepf et al. 2014).

Conway then turns to the insight that "there is darker side to this progress." (p 429) Part of the explanation of progress was learning and improved experience. But the other part of the explanation is "that we were simultaneously climbing an energy ladder." (p 429) There he refers to the fossil trio, coal, crude oil and natural gas. Governments want to bring down CO_2 emissions, which is incredibly ambitious, but he argues that it can be done. Each previous shift made lives easier. However, this time it is the opposite:

> "Except for nuclear power, we are shifting to less dense sources of energy." (p 431)

That is, by the way, one of the arguments added to the presumed climate-neutrality that Conway like many others favours nuclear energy. That is in contrast to his otherwise economic type of arguments. Interesting.

He then turns to hydrogen as a new fuel for the future and then to the materials needed to "engineer our way to net zero." (p 433) In his view "[A]ll roads invariably lead back to the six substances of the Material World." (p 433). That is a type of proof by definition. Actually, he knows better: in some parts of his book Conway is explicit about the needed elements such as cobalt, vanadium and many more metals and semimetals as well as some other elements.

However, Conway did not start at the beginning, the functionalising of all elements of the periodic table. He adds here and there add-hoc some other elements, mainly metals and semimetals, but he does not analyse the material world and how humankind has learned to functionalise the elements of the periodic table. All of them.

Then Conway displays an *exciting future vision*:

> "And it gets better. Because while renewable energy is considerably less dense than fossil fuels, it is nonetheless practically infinite. […] And super-abundant energy opens up a range of other tantalising options. […] We could make synthetic fuels which could power hypersonic planes, cutting the journey time between London and Tokyo to a few hours. With truly plentiful, cheap energy we could even sinter together, smooth spherical grains of desert sand into the rarer angular varieties used in construction." (p 435)

However, he is aware, that it is a vision not easily to be realised:

> "It is a seductive vision. But it will involve a momentous effort and a lot of time and money to get there. There is no single switch we can flick to turn the entire Material World on to renewable energy. And it will necessitate extraordinary amounts of raw materials." (p 435)
>
> "On the basis of one calculation, we will need to mine more copper in the next 22 years than we have in the entirety of the past 5,000 years of human history." (p 436)

This type of future vision is revealing because the underlying thinking is still influential. Then Conway continues with an argument made by the prominent economist William D. Nordhaus: the first generation has to *sacrifice consciously* but only successive generations would reap the results. That is contrary to the facts: *delayed action is the problem.* It does not only cause more troubles –

climate change, degradation of biodiversity, other dimensions of unsustainability – but it is more expensive and really dangerous (Held 2022). Conway uses the misleading frame of sacrifice.

A convincing argument is based on his observation that right now rising geopolitical tensions hamper the needed transformative steps for the energy transition:

> "But on those rare occasions when these supply chains break down, most obviously in the face of war or trade battles, all bets are suddenly off. The Material World rapidly becomes all-important." (pp 437f)

> "But none of this will come as a surprise because by now you will know how much these materials matter. You will know that they represent the foundations of modern life, and that without them we are in deep trouble." (p 438)

He emphasises that policymakers were not prepared yet. They have not even a primitive map about the material flows we are dependent on, a map of the Material World.

He then envisions the ways ahead. He ends the last paragraph of his book with the hope that we

> "are also capable of living far more sustainable, cleaner lives, diminishing our destruction and contamination and living in closer harmony with the planet. We will do so not by eschewing or dismissing the Material World, but by embracing it and understanding it. These six substances helped us survive and thrive. They helped us make magic. They can do it again." (p 443)

Personal notes

Conway writes about the Material World. As outlined, he began to dig into that part of the world because he had the insight that the world, he lived in, was dependent on materials. He named his world as the ethereal world. At the end of his book he writes in a personal note:

> "As someone who has worked my entire life in the ethereal world, enjoying the spoils of the Material World without ever getting my hands dirty, the journey recounted in this book has been somewhat chastening. The more I travelled, the greater the nagging feeling that we have all become disconnected from the primary industries upon which we all rely for our survival." (p 441)

I like it that Conway took his time and experienced the matter of his interest, the mines and production sites all over the world personally. He was fascinated by the "rocks and earth, crystals and strange powders." (p 473) He brought them as souvenirs for his daughters back home which were excited about those raw materials of the earth. He ends the acknowledgements of his book with this fascination born out of own personal experience:

> This wonder and excitement "reminded me what this book was really about: the magic embodied in seemingly simple substances. It turned out to be the most inspirational lesson of all." (p 473)

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