Prof.dr. Ester van der Voet

Imagining the future: building a knowledge base for a sustainable resource use

Universiteit Leiden
The Netherlands

Imagining the future: building a knowledge base for a sustainable resource use

Inaugural Lecture by

Prof.Dr. Ester van der Voet

on the acceptance of her position as Associate Professor

at the chair of Sustainable Resource Use

at Leiden University

on Monday 2 Mei 2022

Universiteit Leiden
The Netherlands

Mevrouw de Rector Magnificus, zeer gewaardeerde toehoorders,

Sustainable resource use – why?
Humanity has used natural resources since the dawn of times, for food, for shelter, for protection, for fuel. Natural resources are essential to support human life and human societies, but their extraction and use is also associated with problems.

For the vast majority of our history humanity had a biobased economy, taking plant and animal resources from the environment to provide for our needs. Later on, our ancestors started to domesticate and grow plants and animals: the agricultural revolution. This allowed for easier access to those plant an animal resources. But it is only since the industrial revolution in the 19th century that our use of resources skyrocketed. The use of coal made it possible to power large scale industrial processes. We shifted from a biobased to a fossil fuel based society. This high quality energy source made it possible to extract, refine and use metals and minerals on a much larger scale as well. Since then, our extraction of resources has grown beyond comparison. And with it, environmental problems grew as well.

This is no news. Already 50 years ago, in 1972, the Club of Rome[1] raised the alarm. If we didn't take action, resource extraction would continue to grow exponentially. We would run out of all kinds of resources and damage the environment by our waste and emissions, to our own detriment. Well, we didn't run out of resources. Here at least they had it wrong. But they were quite right in their estimates of the growth of resource extraction, and also in their alarm around waste and emissions. Now, fifty years later, the insight that the use of coal, oil and gas has many negative impacts is accepted knowledge. Its major waste flow, CO_2, is dumped in the atmosphere and is changing the climate on a planetary level. We know what needs to be done to solve that. We have to shift to other sources of energy, mainly wind and solar. While there are many difficulties along the road, we are at least on our way to actually start doing that.

Resource extraction has skyrocketed not just for fossil fuels, but also for other types of resources. We extract metals and construction minerals, to build houses, roads, railways, electricity and gas distribution grids, telecom infrastructure, sewage pipes etcetera. And to produce all the products we use on a daily basis. About one third of our energy use[2] goes into extraction and production of materials and products. Part of the climate change impacts can therefore be attributed to the materials we use. But there are other problems as well. And those originate especially from the way we use those resources in our economies.

The way we use resources is sometimes called: the linear economy, or the take-make-dispose economy: we take resources out of the ground, make products out of them, use those products once, or for a little while, and then throw them away. This practice leads to huge waste streams, environmental impacts of all kinds, and in some cases even supply problems. Everybody has heard about plastics in the oceans, a large unregulated waste flow that causes a lot of harm. Everybody has heard about disappearing forests, that make place for agricultural land to raise crops for cattle feed. Everybody has also heard about mining and refining sites for metals, where tailings and emissions cause disaster in the local environment. And those are not far-away stories but they happen here as well.

The root cause of this take-make-dispose economy is in our economic system. The prime driving force of our economy is efficiency: producing products and providing services at the least costs. This seems reasonable, but unfortunately, resources are just not part of the economic equation. The price of the materials that are produced from resources is determined mostly by the cost of extracting and refining, but the resources themselves we can get from the environment for free. Since they have no economic value, resources don't count in efficiency calculations. That means that there is hardly any incentive to use less resources. Since resources cost nothing, wasting them is not felt by companies handling them. More efficient production does not mean using less resources. It means reducing labour costs. It has led to automatization and to relocation of production to low wage countries. It has led to globalization. It has led to huge trade flows all over the world – bulk transport is also cheap[3]. But it has not led to a more careful use of resources.

What has in fact happened is that mining and extraction now takes place mainly in developing countries and emergent economies. Europe has become dependent on other parts of the world for many of the resources they use. And that is risky – those other parts of the world have their own agendas. And who can blame them if they take care of that! It's not that we couldn't change that situation. Europe itself has plenty of metals in the ground that could be mined. Yes, it would be more expensive than mining in China, and nobody likes a mine in their back yard. But it could be done if we wanted to, and at the same time we could do a better job in responsible and sustainable mining.

But wherever they come from, the use of these resources is linked to problems of waste and emissions to the environment. There is many things we can do to avoid some of these problems, and many things we already do. Of course it is important to clean up production processes and not litter our waste. But we also need to realise that in a situation where resource extraction continues to grow rapidly worldwide, end-of-the-pipe solutions and a more efficient use of resources is not enough. In the end there is just one inescapable conclusion: the extraction of primary resources needs to be reduced if we want to stay within planetary boundaries[4].

Sustainable resource use - How?

Reducing resource extraction is a tough challenge. And also a challenge to meet very carefully. After all, sustainable resource use has more dimensions than just the environmental one. Sustainability also includes development, health, education, equality, well-being in general, intergenerational justice even. The United Nations have formulated their Sustainable Development Goals, or SDGs in short, 17 of them[5]. Some of the SDGs refer to the environment, like Life on Land, Life under Water, or Climate Action. But others have to do with development: Zero Hunger, No Poverty, or Decent work and economic growth. While for the environmental SDGs it is clear that we need to reduce resource extraction, the development SDGs give another message. No poverty implies decent housing, food and clothing, and access to health care, transport and communication. For that, we need resources. Lots of them. While it is clear resource use has a downside, it is equally clear that resource use provides essential services in the shape of food, shelter, mobility and communication. From the development SDGs, an increased extraction of resources would actually be a good thing.

So here we see a huge tension. Resource extraction damages the planet in many ways. Resource use brings benefits. It is not bad by nature like emissions to the environment. Resource use cannot be avoided, in fact we don't even want to avoid it. So the main challenge for a sustainable resource use can be formulated as: can we reduce resource extraction, but still maintain and even expand the functions these resources fulfil in society?

It will be clear that there are no easy solutions, and the transition towards sustainable resource use may be even more challenging than transition towards renewable energy system. While shifting towards a fossil free energy system is still by-and-large a technological transition, sustainable resource use may imply basic changes in our society as a whole.

Role of academia

Many actors in society have to carry this transition. One of those is academia, that play a vital role in the transition through research and education.

To identify solutions and ways forward, we need research from different disciplines. Technology, environmental science, economics, social and behavioural science, law and political sciences. The research field I am coming from also has an important role to play: industrial ecology[6]. Although I work in that field now for many years, I can imagine you have only a vague idea of what it is. It hasn't been around for that long – only 30 years since its birth, which is short for a field of research. But it offers essential insights to support a sustainable resource use.

The object of study in industrial ecology is our society, our economy. Only it considers the economy in terms of materials and energy, not in terms of money. Industrial ecology is sometimes referred to as: the study of society's metabolism, in analogy of the metabolism of a living organism. To grow and maintain itself, society needs to take in materials and energy. And excretes CO_2 and solid and liquid waste in the process, just like an organism. Goods and services can be described in terms of money, but also in terms of the materials and energy needed to produce or provide them. Trade can be described in terms of kilograms of material as well as in money being made. Consumption can be described in terms of materials and energy, as well as in expenditures.

In fact, industrial ecology acknowledges that the laws of nature also apply in society, and that it has been a mistake to ignore these laws in planning and operating our economies. Industrial ecology has some core methods based on the laws of nature. Material Flow Analysis is a direct application of Lavoisiers law of conservation of mass[7]. What goes in, has to come out again, and if it doesn't, it accumulates, only to come out at a later moment. Life Cycle Assessment, showing all environmental impacts related to a product or service, and therefore showing not just the benefits but also the drawbacks of replacing one product by another[8]. Environmentally Extended Input Output Analysis, attempting a direct connection of mass flows with economic models, showing rebound effects at the national level[9]. By taking such a systems view, industrial ecology methods offer insights that are not always very nice to hear, but are nevertheless useful. Often we industrial ecologists play a role as the party pooper. Whenever someone comes up with THE solution to a problem, industrial ecologists take a look and point out the drawbacks of that solution. I will give some examples later on.

Industrial ecology and the resource challenge

Now we come back to the resource challenge. Industrial ecology approaches this from the resources themselves. From that point of view, resource related problems can be solved in three ways: substitution, consuming less, or moving toward a circular economy.

First, substitution. Problems may be reduced if we substitute one material with another, less problematic material. Immediately the industrial ecologist will ask: this other material, it has impacts as well, since no material exists that is impact free. Is it really better? Or is it just shifting the problem? I will give some examples. Some years ago, replacing fossil fuels with biofuels was considered the solution to the climate problem. Biofuels are made from plant material and therefore count as "climate neutral": the CO_2 that is emitted during use of these fuels is counteracted by the CO_2 uptake of the same plant material earlier. Problem solved! Steep policy goals were formulated for a fast transition to biofuels. But unfortunately, we forgot that we need land to grow these plants. And water, and fertilizer, and tractors, and … . If all the world would shift to biofuels, we would need a couple of planets to grow sufficient crops[10]. This has caused policy to make a turn – biofuels still have a place in the energy transition, but a modest one. A similar discussion is presently ongoing about building and construction. What if we replace concrete and steel in buildings with wood and other biobased materials? That would reduce the climate impacts related to construction materials considerably[11]. But here, as well, the question is: do we have sufficient land to grow the wood? The jury is still out on this one. A third example has to do with our diets. What if we would shift towards a more vegetarian or even vegan diet? Would there be such side-effects as well? The answer to this one is different: this would actually be a very good idea that would not only reduce greenhouse gas emissions, but would reduce land use at the same time. Now, a lot of the crops we grow are used to feed animals, which won't be necessary anymore in a vegan world[12].

The second way out of the resource challenge is to consume less. This would seem an undisputed positive, and would indeed really help. There are still many no-regret changes that could be made to save resources. But here, too, we run up against boundaries. Such as the rebound effect. If we are successful and really consume less, we save expenditures. But what we save in one area, we usually spend in another way. For energy and CO_2, this rebound effect has been established clearly. People save on their energy bill but spend the extra money for example on air travel. In that case, the end result is not better. For resource use, this rebound effect has not been proven yet, but there may be examples as well[13].

There are also examples to the contrary. The price of housing, at least in these parts of the world, goes up like crazy. As a result, people don't move to bigger houses if their families and their income grow. Young adults leave their parental home later, and then live in tiny spaces because it is all they can afford. That is unfortunate. But it has also an upside: fewer square meters of dwelling area per person also implies lower resource use and lower environmental impacts.

The third option to solve the resource challenge is moving towards a circular economy. Before going into that I need to explain – what do I mean with a circular economy? This rather new concept is not yet properly defined and if you just browse the internet many different things come up. In fact the number of definitions of the concept of a circular economy is well above 100[14]. But the purpose is the same in all of them: reducing the need to extract new resources, while maintaining the in-use stocks of products and the functions they fulfil. And that purpose implies a shift of focus from flows to stocks, from demand and supply to the functionality of what already is in the use phase. I'll come back to that later on.

The concept of the circular economy has been operationalized in many ways as well. There is one I like in particular: a circular economy can be reached in three ways: closing the loop, slowing the loop and narrowing the loop[15].

Narrowing the loop is about resource efficiency: providing the same service with a lower material input. Can be because of a lighter design, but also simply by avoiding losses during production.

Slowing the loop is about keeping products in use for a longer period – keep your computers for 7 years instead of 3 before buying a new one, for example. This will lower the demand for new computers while at the same time the number of in-use computers is not going down. A more robust design, or better possibilities for repair, more second-hand use, or simply not throw stuff away so soon, all belong to slowing the loop.

Closing the loop is about recycling. When a product finally becomes waste, instead of dumping it on landfills or incinerating it, we should rather recycle the materials it is made out of so they can be used again, even if in different products. This, too, will result in a lower demand for new materials, and has to potential to reduce emissions considerably[16]

Circular economy is a new concept, so here, the industrial ecology research is still in an early stage. Some party pooper conclusions are already becoming apparent. For example, there is a trade-off for lengthening the life span for energy using products such as refrigerators or cars. The older ones use so much more energy than the new ones, that there is a point where it becomes better for the environment to buy a new one than hanging on to the old one still longer. Obviously this is not the case for, for example, furniture. The longer the life span of your chairs, tables and closets, the better it is.

My research: urban mining and scenarios for resource use
The examples I gave from the industrial ecology field provide information for a sustainable resource use from an industrial ecology perspective: ignoring the laws of nature in society leads to inadequate solutions. Decision making should be based on more information than currently happens. My research, within the field of industrial ecology, aims to provide such information in two areas: information about the urban mine, and information on potential future pathways of resource use. I'll explain.

Let's start with the urban mine. Another new concept, which fits in the circular economy area. Presently we take our resources from the environment. Those resources are applied in all kinds of products and infrastructures. They then become part of the in-use stocks of our society. These stocks remain there, huge amounts of materials locked away in all the stuff we can see around us. Sometimes they stay there for many years, until they become waste. These materials, residing in society in stocks of buildings, infrastructure and appliances, is what we call the urban mine[17]. This is the material we have to work with in a fully circular economy. Important knowledge, yet we know very little about it. These stocks are not accounted for in statistical offices.

One can look at these in-use stock of products as if they were a mine and make plans of how to access this mine. For geological mines, mining companies go through a lengthy process before they start up a new mine. First, exploration: looking for a suitable site where they expect profitable ores in the ground. Then, prospecting: making estimates of how much material is in the ores. If that seems to be interesting, there is a whole suite of activities they have to go through, making business plans, acquiring the land, getting the permits, and once that is in order they have to prepare the site, build factories, sometimes even roads to the site, hire workers, purchase equipment etc. The time from exploration to the actual start-up of the operations can be decades.

For urban mining, a similar sequence of steps needs to be taken. Research is now in the stage of prospecting: trying to find out how much of which materials there are in the in-use stocks in society[18]. These amounts appear to be really large. According to the International Aluminium Institute, 75% of all the aluminium ever extracted in human history is still in use[19]. One of our prime industrial ecologists, Thomas Graedel from Yale university, estimates the copper stock above ground, in the urban mine, is in the same order of magnitude as the copper stock below ground in known geological reserves[20]. Our own research into the urban mine of the Netherlands seems to confirm that statement. That is where we are at present. Slowly we are gaining insight in the size and the nature of our in-use stocks, and how these stocks might develop in the future. Here at Leiden University we investigate in-use stocks at two levels: the level of the Netherlands, and the global level.

In-use stocks are not accounted for by statistical offices. Yet there is a lot of information to be found once you start looking – data from all kinds of sources that we bring together and combine. Together with CBS, our national statistics office, we now have created for the Netherlands a reasonable picture of the materials embedded in buildings, in our energy system, in vehicles, and in a number of different types of products. For the global level, the database is even scantier and we have to work with sometimes rough approaches, but here too we now approach an order-of-magnitude estimate of some of the major in-use stocks[21].

After prospecting comes the mining plan. Here we have to keep in mind that urban mines are different from geological mines in a number of ways. A very important difference is that they are presently in use, so it is not possible to access them straight away. We have to wait until the in-use stocks become waste. That doesn't mean we can just sit and do nothing. While waiting we can plan for it and prepare for it, and put our collection, separation, reuse and recycling systems in order. Important information for the planning is the life span of the applications. That can range from a few weeks in the case of, say, drinking cans to many, many years in the case of buildings and infrastructure. Using these life spans we can visualise the future availability of the materials from the urban mine.

And that brings me to the second topic our group has been working on: scenarios for resource use. The future availability of materials from the urban mine is a part of that, but these scenarios are much broader. The questions we are dealing with are, how might the future demand for resources develop, and how could we supply that? The future demand for resources obviously depends on the population development: how many people will need food, clothing, housing etcetera? It also depends of the development of the national income and on the speed of development. And on the changes we make in our consumption patterns. And on the constraints we will run up against in the supply. Resources from the urban mine form a part of the supply, imaginably and hopefully an increasing part.

We do not see these scenarios as predictions of the future. We are not trying to be as accurate as possible. After all, it is the future we are imagining, which hasn't happened yet. Things may happen that change the direction of development drastically, as we have experienced recently. Rather than predictions, such scenarios are explorations of the future. They will tell us which future pathways might lead to disaster, and which ones might make the world more sustainable. They will provide information on the consequences of certain possible developments, decisions, or policies. Imagination is just as important as facts and knowledge, especially in outlining a future we might actually be able to sustain.

The development of such scenarios requires inputs from many sides. For that reason we are developing them in larger consortia. At the national Dutch level we cooperate with PBL, the Planning Agency for the Environment. We use the already existing projections they provide for population, for national income, for the development of certain sectors, for energy and land use. And we use information from the sectors themselves in how they envisage their future. We have done some explorations already on the future energy system and the future built environment[22] together with them.

At the global level we are connecting with PBL's IMAGE model, one of the major integrated assessment models used for the reports of the Intergovernmental Panel on Climate Change, to support decision making on energy and climate. These models already contain projections for population, for welfare, for the development of the energy sector, for food and land use. In fact what we are doing here is to add a module on resources to the climate models. This allows to include resources in the climate assessments. But it also allows to do explorations of future demand for resources and see the future climate impacts of resource use. Here we have already made steps. The next step, linking that demand to supply, and especially supply from the urban mine, has yet to be taken. To imagine scenarios for a sustainable resource use is done in the context of the Global Resource Outlook reports of the United Nation's International Resource Panel. It is an exciting challenge. Our contribution to it will be especially in the area of including the in-use stocks, the urban mine, and modeling its dynamics.

Some first insights already come from these explorations.

By far the largest stocks of materials can be found in buildings. Most of that is concrete, bricks, stone and other bulk construction minerals. But also large amounts of metals, especially steel, are part of those buildings. Over the last two decades the global demand for these materials has risen rapidly due to the very fast build-up of China's infrastructure. The demand will surely grow further when other countries will do the same, as will the in-use stocks of materials.

Even if all the new buildings from now on will be built according to circular construction principles, it will take a very long time before this will have any effect. Buildings have a long life span. In fact, buildings that we can see now if we look around us will for the majority be still there in 2050. In this optimistic view of the future we are building up a new stock that is wholly recyclable or reusable or otherwise sustainable. And we have an old stock that slowly will become waste, taking many decades or even centuries to empty itself.

Smaller in-use stocks can be found in all kinds of electric and electronic appliances. These stocks have been growing fast and contain some valuable materials. Life spans are relatively short so accessing this particular urban mine could start already. We could make this a test case to develop and try out ideas on all that is needed to make urban mining work.

The system that will probably go through the most changes is the energy system. To prevent climate change from running out of hand, we have to move from coal and gas fired powerplants to solar and wind energy. We have to "get off the gas" for heating and cooking, and move to heat pumps and electric cooking. We have to change from gasoline to electricity for driving. And we have to do that fast. That means we'll need more resources, not less, to build up this new system. Bulk materials like steel and aluminium, but also small scale critical materials for the new energy technologies[23]. Meanwhile, the present energy system will become obsolete, so large outflows out of the urban mine can be expected of all the materials related to coal and gas based power plants, the entire gas grid, and important parts of the oil based industry. Here, too, is a double challenge for the future: building up the new system in such a way that it can be easily reused or recycled, as well as taking care of the waste flows of the old system and put them to good use again wherever possible.

Presently, transporting coal, oil and gas around the world takes up a large part of freight transport. If we move to a renewable energy system, think about all these oil tankers, bulk carriers of coal and gas pipes that will not be needed anymore. But a whole new transport infrastructure may need to be set up for accessing the urban mine, which we presently can imagine only vaguely. There is also some good news to mention from these insights. For the transition towards a sustainable resource use we do have two autonomous developments working in our favour. The first is stabilization of the population. In most scenarios for the future, stabilization of the global population is expected to happen somewhere in this century. That is good news – at least the number of people needing food, shelter and transport won't grow anymore. The second piece of good news is the process of stock saturation. We see that an increased income level leads to more stuff per person. But beyond a certain level of income, that is no longer true. However rich you are, you don't need increased amounts of washing machines, or cars, or houses. And so the in-use stocks of products per person stop growing, or in other words, they saturate[24]. When that happens the demand can go down and the outflow of materials out of the urban mine can catch up with the inflow. It will then be possible to close the loop at least in theory. Our job is to start imagining, designing and implementing our sustainable resource use system as soon as possible, so it will be effective when the time is right.

The message from all this for politics is not an easy one. We need to make changes now, but the benefits are expected only in the future, sometimes even the distant future. Good old-fashioned economics would tell us to discount such benefits. But if we don't make the changes now, we will only move further away from a sustainable society, and it will in the end be so much more difficult to make the transition.

These are some first insights, arising from acknowledging the laws of nature to work also in our society. I'm expecting many more insights to follow from industrial ecologists in the future from their particular view on the material and resource system, and if necessary to fulfill their role as party poopers with conviction. But much more is needed that has to come from other disciplines. Input is needed from technological sciences, on product design so products can be repaired or at least disassembled, and on material design so materials can be recycled[25]. We need input from micro-economics: new businesses have to be established that make it their business to repair, reuse, disassemble, remanufacture and recycle. Presently such businesses run up against all kinds of barriers of legislation, but also of markets and economic incentives that work in the wrong direction. We might have to re-think our economic system altogether, to a system where resources are regarded as valuable, and to a system that will not be blind for long-term consequences. To a system where economic pressure, the equivalent of Darwin's natural selection, operates towards sustainability, not away from it.

So, we conclude that the resource challenge is a large one, and that we need a long term transition for resources as well as for energy. Changing mindsets on such a scale takes time. Other transitions have shown us that. Look at the energy transition. The IPCC started their messages on climate change already 30 years ago[26]. Finally now things start to happen. Abandoning smoking – already since 50 years we know it causes cancer and all kinds of other diseases, and finally now it is banned from many environments. Vegetarianism – also already since decades we know a plant-based diet would reduce environmental problems no end. Only now we see it spreading in society especially among young people.

The time between signalling the problems and having them firmly on society's agenda appears to be in the order of 50 years. It is now 50 years ago since the report of the Club of Rome, so it's high time the resource challenge is acknowledged as an urgent issue in our society!

Acknowledgements

I want to take the opportunity at the end of my speech to say a few words of thanks. Thanks to the Rector and the Board of Leiden University for creating this chair. Thanks to the Faculty board for their support in that process. Thanks to the CML management and in particular CML director Arnold Tukker for taking the initiative.

And then I would like to thank my long-term colleagues, that have provided an inspirational team wherein we contributed to shaping the industrial ecology field over many years. Jeroen, Arjan and Lauran – you have been, and still are, invaluable colleagues and friends. Gjalt, I think you should have been in my position right now, as founding father of industrial ecology's main methodologies. René, you have been my long term "roommate" and partner in so many endeavours, among others the start-up of our Master program, and my touchstone for many ideas.

Thanks also to the present and former PhD students and MSc students that work with me and add their considerable skills and knowledge to this field. Among many others Sebastiaan, Janneke and Teun, you have been invaluable in shaping the field we work on together. Thanks to colleagues at TU Delft that have been partners in our Masters program, some from the start: Gijsbert, Karel, Jaco, Andrea and Linda. Thanks to my dear colleagues from our international Masters programs MIND and CIRCLE: Ralf, Ulrika and Johan, Anja and Ulrike, and also Yasushi who has been part of it from the start. Thanks to the support staff at CML, among others Esther, Jasper, Suus and Sammy, Paul, Kiki, Paula, Marleen and Joyce – without

you all our research and education would not be possible.

Thanks also to my younger colleagues at CML, our next generation. Among others Stefano and Tomer, it is a pleasure working with you and remember, it's up to you to carry this field forward! Thanks to the many inspirational colleagues from elsewhere I have encountered during my career, colleagues from PBL, from the International Society of Industrial Ecology, from the International Resource Panel, colleagues from other universities and research institutes that I have worked with in research and education projects over the years.

Finally thanks to my dear family and my friends, and thanks to my partner in life Ruben, for their unwavering support throughout my professional and personal life.

Ik heb gezegd.

Eindnoten

1 Meadows, D.H., D.L. Meadows, J. Randers, W.W. Behrens III, 1972. The Limits to Growth, a report for the Club of Rome's project on the predicament of mankind. Universe Books New York, ISBN 0-87663-165-0

2 Oberle, B., S Bringezu, S Hatfield-Dodds, S Hellweg, H Schandl, J Clement, L Cabernard, N Che, D Chen, H Droz-Georget, P Ekins, M Fischer-Kowalski, M Florke, S Frank, A Froemelt, A Geschke, M Haupt, P Havlik, R Hufner, M Lenzen, M Lieber, B Liu, Y Lu, S Lutter, J Mehr, A Miatto, D Newth, C Oberschelp, M Obersteiner, S Pfister, E Picoli, R Schaldach, J Schungel, T Sonderegger, A Sudheshwar, H Tanikawa, E van der Voet, C Walker, J West, Z Wang, B Zhu (2019). Global Resources Outlook 2019: Natural Resources for the Future We Want. UNEP – IRP, https://resourcepanel.org/reports/global-resources-outlook

3 Kleijn, E.G.M., 2012. Materials and energy: a story of linkages. Doctoral thesis defended 2012-09-05, Leiden University.

4 Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin III, Eric F. Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, Björn Nykvist, Cynthia A. de Wit, Terry Hughes, Sander van der Leeuw, Henning Rodhe, Sverker Sörlin, Peter K. Snyder, Robert Costanza, Uno Svedin, Malin Falkenmark, Louise Karlberg, Robert W. Corell, Victoria J. Fabry, James Hansen, Brian Walker, Diana Liverman, Katherine Richardson, Paul Crutzen & Jonathan A. Foley, 2009. A safe operating space for humanity. Nature 461, 472-475. https://doi.org/10.1038/461472a

5 https://sdgs.un.org/goals

6 Ayres, R.U & L.W. Ayres (eds.), 2002. A handbook of industrial ecology. Edward Elgar publishers, Cheltenham UK, Northampton MA USA, ISBN 1 84064 506 7

7 Van der Voet, E., 1996. Substances from cradle to grave. Doctoral thesis defended 1996-05-28, Leiden University.
Baccini, P. and P.H. Brunner, 2012. Metabolism of the Anthroposphere: Analysis, Evaluation, Design. MIT press, Cambridge, USA.

8 Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J., 2002. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 692 pp.

9 Suh, S. (ed.), 2009. Handbook of Input-Output Economics in Industrial Ecology. Springer Dordrecht Netherlands, series Eco-Efficiency in Industry and Science, ISBN 978-1-4020-4083-2

10 Kleiner, K., 2008. The backlash against biofuels. Nature Climate Change Vol 2 pp 9-11.
Van der Voet, E., R.J. Lifset and L. Luo (2010) Life-cycle assessment of biofuels, convergence and divergence. Biofuels1(3):435-449.

11 Yadav, M., M. Agarwal, 2021. Biobased building materials for sustainable future: An overview. Materials Today Proceedings Vol 43, Part 5, pp 2895-2902, https://doi.org/10.1016/j.matpr.2021.01.165.

12 Sun, Zhongxiao, Laura Scherer, Arnold Tukker, Seth A. Spawn-Lee, Martin Bruckner, Holly K. Gibbs & Paul Behrens, 2022. Dietary change in high-income nations alone can lead to substantial double climate dividend. Nature Food volume 3, pages29–37.

13 Font Vivanco, D., E. van der Voet & R. Kemp (2015), The relativity of eco-innovation: environmental rebound effects from past transport innovations in Europe. Journal of Cleaner Production, Volume 101, 15 August 2015, 71–85. DOI: 10.1016/j.energy.2011.07.003

14 Kirchherr, J., D. Reike and M. Hekkert, 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation & Recycling 127, http://dx.doi.org/10.1016/j.resconrec.2017.09.005

15 Konietzko, J., Bocken, N.M.P., Hultink, E.J. 2020. Circular ecosystem innovation: An initial set of principles. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2019.119942
16 Van der Voet, E., L. van Oers, M. Verboon & K. Kuipers (2019). Environmental Implications of Demand Scenarios for Metals, Methodology and Application to Seven Major Metals. Journal of Industrial Ecology, 23(1) pp 141-155, DOI: 10.1111/jiec.12722
17 Tanikawa, H., T. Fishman, K. Okuoka & K. Sugimoto, 2015. The weight of society over time and space: a comprehensive account of the construction material stock of Japan, 1945-2010. Journal of Industrial Ecology 19(5) 778-791, https://doi.org/10.1111/jiec.12284
18 Heeren, N. & T. Fishman, 2019. A database seed for a community-driven material intensity research platform. Scientific Data 6(2019) article no 23. Open access: https://www.nature.com/articles/s41597-019-0021-x
19 https://international-aluminium.org/aluminium-industry-optimism-lies-ahead-post-covid/
20 Rauch. J.N. & T.E. Graedel, 2007. Earth's anthropobiogeochemical copper cycle. Global Biogeochemical Cycles Vol 21 GB 2010t, doi:10.1029/2006GB002850
21 Deetman, S.P., 2021. Stock-driven Scenarios on Global Material Demand, the story of a Lifetime. Doctoral thesis defended 2021-12-08, Leiden University
22 Van Oorschot, J., B. Sprecher, B. Roelofs, J. van der Horst, E. van der Voet (2022). Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system. Resources, Conservation and Recycling 178 (2022) 106105
Verhagen, T., E. van der Voet & B. Sprecher, 2020. Alternatives for natural-gas-based heating systems: A quantitative GIS-based analysis of climate impacts and financial feasibility. Journal of Industrial Ecology 25(1) 219-232, DOI: 10.111 ISBN : 0-662-19821-2 1/jiec.13047
23 Liang, Y., R. Kleijn, A. Tukker & E. van der Voet (2022). Material requirements for low-carbon energy technologies: a quantitative review. Renewable and Sustainable Energy Reviews Vol 161, June 2022, 112334
24 Pauliuk, S., R. Milford, D.B. Müller & J. Allwood, 2013. The steel scrap age. Environmental Science and Technology 2013, 47, 3448−3454, x.doi.org/10.1021/es303149z
25 Bakker, C.A., R. Mugge, C. Boks, M. Oguchi, 2020. Understanding and managing product lifetimes in support of a circular economy. Journal of Cleaner Production Vol 279, 123764, 10.1016/j.jclepro.2020.123764
Gözde Dere, E. Sharma H., Petrov R.H., Sietsma, J., S.E. Offerman, 2016. Effect of niobium and grain boundary density on the fire resistance of Fe–C–Mn steel. Scripta Materialia Volume 68, Issue 8, Pages 651-654
26 Intergovernmental Panel on Climate Change, 1992. Climate Change: The IPCC 1990 and 1992 Assessments. Printed in Canada, ISBN: 0-662-19821-2

Prof.dr. Ester van der Voet

Ester van der Voet holds the Chair Sustainable Resource Use in Leiden University at the Department Industrial Ecology of the Institute of Environmental Sciences (CML). Within the field of Industrial Ecology, she specialises in methodology development (life-cycle assessment, material flow analysis, substance flow analysis, natural resource accounting, and indicator development). These methodologies she applies to different topical areas, specifically resource use and resource management, resource efficiency, metals, critical materials, and the circular economy, as well as agriculture and the biobased economy. She has initiated three MSc programs in Industrial Ecology and circular economy: a joint degree program between Leiden University and TU Delft, and two international programs with partners from EU, US, China, Japan and Australia. She has conducted and led many research projects for the EU and in other international consortia. She is a member of UN's International Resource Panel. Her present activities mainly focus on circular economy and urban mining, specifically scenario development at different scale levels and building up information systems to support local, national and international policies on sustainable resource use.

Universiteit Leiden
The Netherlands