Material efficiency is not a panacea, but it lies at the intersection of many problems of global sustainability. Reducing the usage of a single material in a value chain may require ingenuity and wide cooperation, but conceptually it is not a problem. When the problem stretches to several resources in changing circumstances, we have to understand the linkages between resources and the power, and the influence of each resource in decision-making in different settings. In this paper, we concisely go from the time dimension to a very short history of resource thinking, and then introduce our resource convergence concept. Using text mining on a sample of articles linking different resources, we show in a ‘visual literature review’ how resource convergence emerges from unrelated texts. To demonstrate one new method under the resource convergence umbrella, we use a case example with our Resource Power Index method. In our opinion, mastering complexity will be the key to solving the challenges we are facing, and mastering resource convergence and translating it into material efficiency is one of the central problems. What we show in this paper is a core framework and some details of the direction we see as worth pursuing.

1. Introduction

Once upon a time, not so many years ago, the word of the day was dematerialization [1]. Matter flows were going to disappear, and in their place digital bits would, in their binary elegance, provide the driving force, medium, value and content of life.

However, somebody noticed that even the most fashionable digital devices are but points in a stream of material flows, and that natural resources that had lain dormant outside public opinion suddenly were key to these matter flows [2].
Of course, dematerialization is not a consensus opinion around an extreme. As an example, the Factor 10 Club definition of using 90 per cent less resources for the same level of wealth and welfare gives a moderate version.

In spite of the triumph of the Internet, social media and similar phenomena, we are back in a resource world, where nations compete in finding and extracting natural resources because of their hunger for material goods, some of which enable enjoyment of digital content.

From European Union (EU) resource efficiency flagships to resource savings initiatives, material efficiency emerges as the platform to sustain our changing life habits on Earth. Providing material and digital services with less material production is a simple solution, but the implementation, even changing the viewpoint, is another story [3,4].

(a) Goal of this article

As we introduce a new concept (resource convergence) and a related new adapted algorithm—the Resource Power Index (ReP)—we have the goal (and problem) of laying a sufficient foundation, explaining the concept, placing it in the context of material efficiency, demonstrating the new algorithm and pointing ways forward in quite a limited space. In attempting this, our logic is as follows.

(i) Positioning the concept in two timelines of history: that of human endeavour and the much shorter one of recent material efficiency thinking

Using the history of the Maya of Mesoamerica makes it possible to introduce the impact of biomass yield (currently a highly topical aspect of material efficiency), rainforest destruction and value added as determinants of history. At the same time, a perspective of analogy can be brought to bear on the Maya storyline as well as recent developments in environmental and material efficiency thinking.

*Foundation established*: there is little new with regard to material efficiency, but a pattern of swings back and forth in resource thinking has been apparent in the last few decades.

(ii) Presenting the resource convergence concept

The concept itself is presented and a short history of converging natural resource strands is examined.

*Foundation established*: a chain of evidence for the parallel and complicated development in natural resource linking in the econosphere and envirosphere.

(iii) Positioning resource convergence in relation to complexity theory and the economics of high technology

As technology would seem to be an integral part of material efficiency, schools of economics have focused on complexity theory, and the economics of high technology is touched upon through the works of Arthur. The related concept of the technium is also mentioned.

*Foundation established*: complexity theory is a new influence, and is not yet in the mainstream of economic thinking. The core component of things assembling themselves and patterns emerging from interacting elements is of key importance in dealing with resource convergence and related emerging phenomena.

(iv) Positioning resource convergence as an emerging phenomenon through a semantic analysis of the scientific literature

Using semantic text mining on a selected set of scientific texts, a semantic network between the concepts is produced.
Foundation established: the semantic network from the text analysis shows an emerging pattern of resource convergence as defined in this article.

(v) Positioning resource convergence and our approach in relation to material efficiency

The concept presented and its relationship with and impact on material efficiency are assessed, starting from definitions and continuing with a very concise discussion on the ways to assess material efficiency with complexity theory. As a first application, the ReP algorithm, a modification of the Banzhaf algorithm from political science, is presented and an example is given.

Foundation established: the relationship between resource convergence, complexity and the impact on ways to assess material efficiency is assessed. A new algorithm potentially serving several purposes in material efficiency is presented.

(vi) Discussing the next steps

Finally, we discuss the next steps among many possible ones in this merger of mathematical, conceptual and resource thinking.

In what follows, we present our approach, concept and demonstration algorithm following this process.

2. A very short timeline of resource thinking

(a) From Smoking Frog to Ah Cacao

As a material and resource efficiency case with parallels to the current situation, let us take as an example the Maya of Mesoamerica. The simplified step-by-step process below describes the events and perceptions of a part of Maya history. The literature on the Maya is very rich; for a summary of what follows see Fernández-Armesto [5].

(i) Step 1. Misperception: wonderful peace and harmony

During the nineteenth century and most of the twentieth century, the Maya were imagined by Western scholars as a philosophical, harmonious, peace-loving civilization of astronomers. Thompson [6] was a leading Mesoamerican archaeologist, ethnohistorian and epigrapher, and a leading champion of this school of thought. However, the perception of peace proved to be untrue, and the Maya were at the very least not below average and perhaps even above the norm in war-like activities. In the next step, we jump back in time to the actual events.

(ii) Step 2. Truth: yield in food production giving advantage in wars

The history of the Maya is riddled with continuous wars over territory and sacrificial victims. A key advantage was material efficiency: Tikal, a major city, had a yield advantage in food production, which in turn led to more and better fed warriors. An indication of these wars is given in the record of the installation of a noble from Tikal, Smoking Frog, as ruler of nearby Uaxactun in AD 378.

(iii) Step 3. Truth: decay with rainforest destruction as a cause

Wars and ruthless destruction of rainforests by the Maya, the self-styled ‘Lords of the forest’, caused a seemingly irreversible decline.

(iv) Step 4. Value added: greater eco-efficiency ratio ‘value/environmental impact’

In AD 682, a ruler named Ah Cacao (personal glyph: a chocolate pod) ascended a city throne, and steered exports towards the high-value-added chocolate. An innovation in soil management for cacao is theorized to have occurred.
After these events, many steps occurred, but the story of the Maya is not at an end, with a misinterpretation of the Maya calendar making 2012 a ‘supernatural’ year.

(b) From life cycle assessment through carbon to resources

Building a similar stepwise story for material efficiency and linked resource thinking, we have the following.

(i) Step 1. Misperception: a farewell to resources

Dematerialization is seen as occurring: from transport of ore and use of energy to streams of zeros and ones in the ether. This has proven to be untrue. In the next step we jump back in time to tool and related thinking development.

(ii) Step 2. Tool: assessing the environmental impact of the life cycle of a product or service

From the 1970s onwards, steps towards developing tools for comparing the relative environmental impacts of products along their whole life cycle have been taken, leading to standardization work. The focus is on a very broad range of impacts. However, hidden assumptions and overinterpretation of results are among the things that have blackened the reputation of life cycle assessment (LCA) [7].

(iii) Step 3. Tool: carbon footprint

Climate change has risen to unforeseen heights in global attention, and carbon footprint, which is a ‘single-minded’ relation of LCA, has come to the fore [8].

(iv) Step 4. Tool: material efficiency and resource management

A water footprint methodology has appeared and further development has occurred [9]. It is as ‘single-minded’ as a carbon footprint, but the joint appearance of carbon and water tools on the scene has twisted the viewpoint back towards a broader impact perspective, as in LCAs originally. Likewise, the realization that bits only move if they have massive material and energy flows to support them heightens awareness of material efficiency needs.

3. The resource convergence concept

(a) Looking at the whole

There are, of course, many ways of seeing the ‘bigger picture’. These range from, for example, initiatives on an EU scale to new concepts.

On the EU scale, the Innovation Union [10] initiative highlights resource intelligence. Explicit emphasis is on the need for ‘innovation […] in order to increase resource productivity and sustainable substitution while simultaneously reducing resource use and energy consumption […]’ [The committee] stresses the importance of the Resource-Efficient Europe flagship initiative and of efforts to decouple economic growth from the use of resources by supporting the shift towards a low-carbon economy, increasing the use of renewable energy sources’. The concept is more inclusive than the explanation. On a, for the EU, more practical level, the EU Waste Framework Directive (2008/98/EC) introduces life cycle thinking that includes extending product life as a prioritized option.

On the conceptual scale, one could say that we went from an LCA viewpoint to a carbon viewpoint; the carbon viewpoint is challenged by the water viewpoint; and both are challenged by the total resource viewpoint. For moves towards the latter, see, for example, the water, energy, food/fibre linkages pathway proposed by the World Business Council for Sustainable Development [11].
(b) The concept defined

(i) Media convergence

Media convergence has been defined as follows [12]:

> We are living in an age when changes in communications, storytelling and information technologies are reshaping almost every aspect of contemporary life—including how we create, consume, learn, and interact with each other. A whole range of new technologies enable consumers to archive, annotate, appropriate, and recirculate media content and in the process, these technologies have altered the ways that consumers interact with core institutions of government, education, and commerce.

This convergence is marked, for example, by technologies and devices converging towards platforms that enable recirculation of and interaction with digital content.

(ii) Definition of resource convergence

A phenomenon that, in our opinion, is of far greater significance but that attracts less media attention is what we call resource convergence. It can be defined, analogously, as resources, habits and processing technologies converging towards platforms that enable substitution of and new interactions with physical resources.

Resource convergence is proceeding with increasing speed. From a strict separation between industrial sectors and raw materials, the industrial sectors either are being forced or are sometimes willing to reconsider their borders; and raw materials and providers are driven together by interconnections among the product, trade, political and consumer levels.

Illustrating resource convergence in practice in an economic context is, in effect, a reversal of a very entrenched ‘East is East, and West is West, and never the twain shall meet’ [13] position, which can be illustrated in the economic sphere by numerous shifts, e.g.

> — from a complete separation between consumer electronics and biomass to bioplastics and bio-based paints in, for example, mobile phones;
> — from a purely biomass-based world in publishing to managing the biomass (paper) ecosystem and the electronics (energy, metals) ecosystem simultaneously;
> — from a fossil-based energy production to a mixture of fossil and biomass raw material for many energy producers; and
> — from a metal- and mass-oriented activity in mining to a strong awareness of the metal/water linkage.

(iii) Taking the resource convergence definition apart

We defined resource convergence as resources, habits and processing technologies converging towards platforms that enable substitution of and new interaction with physical resources. Let us break the definition down into its components:

> — Resources: natural resources (see §3c).
> — Habits: ways of doing things. A new recycling system or even an emerging culture of separating waste at source at home is a habit. Media convergence plays its role here; social media may have a role to play in reinforcing habit change.
> — Processing technologies: there is a technology orientation coupled with social orientation in the definition. The range of technologies is very wide, from learning robots with machine vision separating waste, through water-purification chemicals, to, for example, nano-biotechnology.
> — Platforms: conceptual (thinking framework, calculation and measurement methods) and physical (technology, social network, ecosystem) foundations for assessment. Examples
could be both a social media platform for finding drinking water fountains instead of buying plastic water bottles [14] or a physical recycling platform at a major port with multiple integrated technologies.

— **Substitution**: especially substitution of fossil-based with bio-based raw materials and substitution of rare metals with bio-based substitutes.

— **New interaction with resources**: dealing in an integrated fashion with multiple external resource streams and internal sidestreams at a single facility.

At the moment, perhaps the most sophisticated such physical resource convergence platform is a biorefinery. The definition of biorefinery has unfortunately not been agreed on. An example is the National Renewable Energy Laboratory definition of a biorefinery as ‘a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass’. A modern kraft pulp mill, i.e. a mill producing wood pulp for paper, paperboard, packaging and tissue, is by this definition a biorefinery; it produces wood pulp (biopolymers), chemicals/biofuels, such as tall oil, and power, resulting in an electricity surplus. Pilots exist for many additions to this platform: biodiesel on-site from tall oil (e.g. the upcoming UPM BioVerno project; http://www.upm.com/EN/ABOUT-UPM/Businesses/Biofuels/biorefinery-investment/product/Pages/default.aspx), different ‘kidney’ technologies for extracting metals from the mass flow and so on. A further developed biorefinery of this type can change production depending on the market situation, perform substitution on-site and process varied content streams of biomass and waste into multiple resources.

(c) A tale of three strands

How many natural resources are there? A pointless question here; the issue is not creating a ‘periodic table’ of resources with clearly defined boundaries. Instead, we are dealing with key groups of resources, where the commonly used definitions sometimes overlap. The main resource groups converging in our concept are

— **biomass**: wood-based, agro-based, marine-based biomass;

— **energy**: resources converted to energy, and energy generated in various forms;

— **water**: $H_2O$;

— **land**: a certain specifiable area of land on Earth;

— **chemicals**: chemical compounds not covered in other resource groups; and

— **metals**: a chemical element, compound or alloy conducting electricity and heat well.

Obviously, the ecosystem of human activity and natural resources refuses to go down neat and oversimplified paths. Interaction in resource convergence is possible between all resources. However, in keeping with the timeline/climate approach, a combination of many climates, such as

— the political and economic climate, because many actions are driven by political decisions,

— the opinion climate, which influences political and market decisions, and

— Earth’s climate and climate change, and the notorious difficulty of climate physics,

has contributed to a certain development, which we can split into three strands with links to the others.

(i) The biomass/energy convergent strand

The history of energy production from biomass through, for example, digestion and incineration is, to put it mildly, exceedingly long. However, the rise of climate change awareness brought bioenergy to the fore. The convergence between biomass and energy can be said to have been in the lead of the recent three-stranded story of resource convergence. Examples vary from using food and animal feed to produce energy, to using residues from the existing biomass value chains for energy and developing new feedstocks purely for energy production [15–19].
(ii) The water/land convergence strand

In parallel, the problem of the availability of water and land of sufficient quality has gained more attention, closely following the first strand of biomass and energy on the timeline. Water and land converge with each other; a good example is cotton production, e.g. in northern India. The link to energy and biomass is easy to understand with both water and land being needed for the production of the biomass that is used for energy [16]. The land/biomass dilemma has already been demonstrated in the Maya timeline earlier in this article. In addition, energy can be produced from water. This however often requires dams or artificial lakes, which in turn require land. The use of water for energy production also has implications for biomass production, when, for example, natural frequencies of floods in riverbanks are used in agriculture [20]. Water in itself is a commodity that challenges the basics of economics with the well-known diamond–water paradox [21,22]. In addition, it is possible that, by conserving energy, water can also be conserved, but, at the same time, conserving water in industrial processes (e.g. enhanced recycling of water) means that more energy is required [23].

(iii) The chemical/metal strand

Chemicals and metals can be seen as the third strand fast approaching the other two. Metals are increasingly being replaced by biomaterials, which require the above-mentioned land and water [24–29]. Metals are also used in water treatment [30–32]. On the other hand, extensive amounts of water are required in most of the metal mines, and there are known issues with mines in water pollution [33]. In addition, mining requires land, and land usage issues are connected to mining [34]. Moreover, interest in producing bio-based chemicals has been increasing, especially in Western countries [17]. This connects chemicals again to land and water, and such production competes for biomass resources with energy and metals.

The above is a very concise, simplified picture and its deficiencies are acknowledged by us—but there is insufficient space in this article to go deeper into examples and complications, and it would not change the concept in itself. Figure 1 summarizes the three-stranded story of resource convergence.
(d) Towards new material efficiency and resource thinking concepts

(i) Complexity economics

It would be preferable to emulate Ah Cacao in the Maya timeline, and go towards higher value-added products with smaller total environmental impact. It should be noted that we here use the Ah Cacao example symbolically, without having performed an assessment of its environmental impacts, or even having data on the exact soil management and chocolate value chain and life cycles of the Maya.

New theories of economics have had a hard time battling neoclassical economics. However, increasing returns economics, behavioural economics, evolutionary game theory and complexity economics are among the new schools of economic thought that have a common ground in, for example, opposition to the view of the hyper-rational *homo economicus*. The economic crisis we are currently living through is likely to increase the research in these new areas.

Arthur [35] is a leading figure in both the economics of increasing returns and complexity economics (e.g. his seminal paper [36]).

Some key statements from Arthur [36] illustrate our thinking on the impacts of resource convergence.

- **Multiple resources**: common to all, studies on complexity are systems with multiple elements adapting or reacting to the pattern these elements create.
- **Constantly changing equilibria**: time enters naturally here via adjustment and change: as the elements react, the aggregate changes, as the aggregate changes, elements react anew. Barring some asymptotic state or equilibrium reached, complex systems are systems in process, systems that constantly evolve and unfold over time.
- **Economic ecosystems as an example**: such systems arise naturally in the economy. Economic agents, be they banks, consumers, firms, or investors, continually adjust their market moves, buying decisions, prices and forecasts to the situation these moves or decisions or prices or forecasts together create.

Hence, the fundamental thinking in complexity economics is closely related to how we see the consequences of resource convergence, and the demands on research and theories to deal with it. Resource convergence leads to a system with the treatment of multiple elements/resources adapting to the pattern that these elements create. The interplay between political and economic actors and natural resources is conducive to constantly changing equilibria. Economic systems are here shifted to political–economic systems with multiple types of actors in many sectors of activity dealing with emerging patterns of interaction between natural resources.

The role of technology is crucial in resource convergence. In the path to new resource thinking, issues arising are embodied, for example, in the *technium* approach of Kelly.

**Emergence and convergence.** Emergent properties are a key part of complexity. So, even though the words themselves are not easily confused, perhaps it is useful here to make the distinction between emergence/emergent and convergence/convergent:

- **Emergence**: emergent entities (properties or substances) ‘arise’ out of more fundamental entities, and yet are ‘novel’ or ‘irreducible’ with respect to them [37].
- **In the resource convergence context**: new behaviour emerges as a property of the politico-economical resource ecosystem, when resource thinking changes and resources are seen as one whole.

**Convergence**: from many different usages of the word in different disciplines, let us here take one, bioconvergence innovation [38]:

BioConvergence Innovation is a paradigm where discovery and technology creation occur at the intersection of biotechnology, chemistry, nanotechnology, the physical and information sciences. Firms and researchers will cross the boundaries between these disciplines to create technological value—finding solutions to
address health, environmental and energy challenges across markets. In parallel will be the emergence of new models of collaboration to enable knowledge creation and knowledge dissemination. Central to BioConvergence Innovation will be a determination of the common value of knowledge versus the private value of knowledge across the associated disciplines—with the goal of advancing and commercializing technology.

For resource convergence, new behaviour and discoveries occur at the intersection of human economic and political action and the natural resource ecosystem.

(ii) The technium approach

Kelly [39] in his book *What Technology Wants* presents the idea of the *technium* as the seventh kingdom of life. In an interview (http://www.treehugger.com/treehugger-radio/kevin-kelly-on-(what-technology-wants-podcast.html) Kelly explains the technium as follows:

TreeHugger: The big idea is this thing that you call the technium, which you say is like the seventh kingdom of life. What is the technium?

Kevin Kelly: The technium is the system of all the technologies, all the things that we have invented, the sphere of manufactured things that surround us. And I indicate by the word technium that it’s more than just, say, the devices in your pocket. It’s more than just the stuff that was invented after you were born, or the stuff that doesn’t quite work yet. And it’s also more than just the physical stuff: the concrete in the world and the automobiles. It includes the intangibles like the calendar or the laws that we make and, of course, software.

But besides all that, [...] I’m using the word technium to indicate that all these things are codependent upon each other. That they kind of form a large ecosystem, if you want to think of it that way, a network of artifacts that are necessary for each other. And that this whole thing has a behavior that none of the parts have, and that we should be aware of what that behavior is.

The above quotation and the book do not by themselves give an easily applicable recipe for applying the technium approach to resource and material efficiency thinking. However, what we want to lift out here is that the *interaction between resources and the technology–culture ecosystem* Kelly describes is an important component of the next step in resource thinking.

(e) Emerging networks of combinations: testing the concept with a visual literature review

A good way to test whether there is indeed evidence for the resource convergence concept in scientific literature is to take a sample of recent scientific articles, publications and patents combining different resources, and see what kind of network emerges through a semantic analysis. This could be called ‘crowdsourcing the scientific metamind’, if one were prone to current media talk. Actually, semantically analysing groups of different texts reveals, through sound mathematical algorithms, underlying relationships. Text mining of this type underlies a variety of applications from adaptive news services (e.g. News360) to, for example, analyses of different sectors, e.g. the biomedical sector [40].

Our sample of articles, publications and patents, and the resources they combine, are outlined in table 1.

Figure 2 shows a partial network of concepts that emerges from the literature review. As is logical, a connecting arrow between concepts signifies a connection in the source texts.

This ‘visual literature review summary’ encapsulates what the articles, patents and other texts in table 1 together signify: even in this sample, a natural linkage forms between biomass, biofuels, energy, water, metals and food (which plays a large role in biomass, land and other resource discussions, and which will in all likelihood further increase its influence).

The network is a ‘crowdsourced’ viewpoint with all input items of equal weight—and the overlaps also appear in this top-level view. Going deeper into the text would reveal further connections, but the above should suffice as a test of concept.
Table 1. Combinatorial texts: analysed sample moving towards resource convergence.

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<tr>
<th>water</th>
<th>carbon</th>
<th>energy</th>
<th>biomass</th>
<th>biofuels</th>
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<td>Arkema/Toyobo press release on the development of high-temperature polyamides from renewable resources [24]</td>
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<td>sustainable biocomposites from renewable resources: opportunities and challenges in the green materials world [45]</td>
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<td>natural-fibre-reinforced polymer composites in automotive applications [29]</td>
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<td>biofuels versus food production: does biofuel production increase food prices? [46]</td>
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<td>boosting biofuel crops could threaten food security [47]</td>
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<td>environmental costs and benefits of transportation biofuel production from food- and lignocellulose-based energy crops [18]</td>
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<td>the path forward for biofuels and biomaterials [19]</td>
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<td>PHA bioplastic: a value-added coproduct for biomass biorefineries [48]</td>
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<td>water purification with rare metals [30,31]</td>
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<td>the development and functions of silver in water purification and disease control [32]</td>
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<td>reducing mine water requirements [33]</td>
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<td>energy-critical elements [49]</td>
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4. Impact of resource convergence thinking on material efficiency

(a) Definitions

A summary of definitions is extremely useful in placing resource convergence into context. The ones below have been picked verbatim from their respective sources.

— Energy efficiency improvements ‘refer to a reduction in the energy used for a given service (heating, lighting, etc.), or level of activity’ [50].

— Resource efficiency means ‘reducing the environmental impact of the consumption and production of goods and services over their full life cycle. The “doing more with less” slogan indicates the focus on more outputs with fewer impacts (fewer resources, less pollution, fewer impacts on the conditions of poor people). Efficiency gains do, however, not guarantee that the overall outcome stays within the ecological carrying capacity of the Earth. Influencing the demand side is therefore another prerequisite for sustainable development. It will only be by a combination of resource efficiency and resource sufficiency measures that the ultimate goal of sustainable consumption and production patterns can be achieved’ [51].

‘The [Organization for Economic Cooperation and Development] has called eco-efficiency the efficiency with which ecological resources are used to meet human needs and defines it as a ratio of an output (the value of products and services produced by a firm, sector or economy as a whole) divided by the input (the sum of environmental pressures generated by the firm, the sector or the economy). The European Environment Agency . . ., which intends to use eco-efficiency indicators to quantify progress toward sustainability on the macro-level, defines eco-efficiency as more welfare from less nature and says it comes through decoupling resource use and pollutant release from economic development’ [52].

‘Eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth’s estimated carrying capacity’ [52].

All definitions above are hard to argue against. The problem, rather, lies in the implementation of the admirable ideas embodied in the definitions.

(b) New aspects on quantifying material efficiency

(i) Changes and ‘the curse of dimensionality’

Obviously, a move to material efficiency necessitates both a change in perspective and new tools or modifications of old ones. This will have an impact on
— the fairly fragmented field of indicators and methods, from carbon and water footprints and their parent, LCA, to
— methods of lesser spread but in a certain sense limited focus, such as material intensity per service unit, and
— interpretation and making results understandable.

‘The curse of dimensionality’ is one name for the syndrome of additional complications and behaviour appearing with high-dimensional spaces. It is definitely present in efforts to make a fuller picture of reality comprehensible to an audience accustomed to one single number from a carbon footprint.

(ii) Complexity, resource convergence and material efficiency

This article does not have enough space for a longer discourse on the impacts on a wide spectrum of assessments. Instead, we focus on one method we have developed ourselves: the ReP. Before going into more detail about ReP, let us spell out some of the linkages, problems to solve and future directions for resource convergence in material efficiency. We have already tested the concept by seeing its pattern emerge from a concise but broad range literature review; let us now test the linkage further.

1. Different tools for specific uses in material efficiency related to resource convergence.

   The climate change focus is evidence of a drive towards simplicity: simple, restricted goals (carbon, ‘20/20 in 2020’). For a certain high level of goals this is obviously needed. However, the natural resource world is not simple. The trade-offs and interactions between resources easily lead to a game of sweeping things under the carpet, finding them and sweeping something else under the next carpet. There is a need in material efficiency calculations for tools that take complexity into account and that can be used to assess and evaluate patterns of behaviour that emerge from complex interactions. A topical example is the relationship between biofuels and food crises, where different estimates of the relationship, which includes at least biomass, energy, water, land and chemicals, have been given (http://www.guardian.co.uk/environment/2008/jul/03/biofuels.renewableenergy). Weighing trade-offs and assessing the importance of resources in material efficiency decisions (see ReP in what follows) is a key need. It is obviously possible to carry out fully functional and credible material efficiency assessments with a simpler toolkit, when the problem definition is more restricted. However, the complex material efficiency toolkit is sadly deficient at the moment.

2. Assumptions around material efficiency and resource convergence.

   The current global economic balance, precarious though it is, rests on a growing China importing very large amounts of resources, processing part of them for internal use and part for export. The sheer volumes involved have created a situation where, for example, a Chinese intensified action can reverberate around the world. Two examples may suffice. The Chinese recovered paper procurement network in Europe is quite sophisticated. With swings in cartonboard production, Chinese companies may suddenly enter the European market with 1+ million ton purchases, which would badly disturb the European recycling balance, including plastics recycling (plastics need paper fibre as a support for incineration). Another example: Chinese purchases of cotton prompted India to announce a short ban on cotton exports on 6 March 2012 (http://online.wsj.com/article/SB1000142405297020345804577262723464381722.html). Linked to Indian problems with water supply and pesticides in key cotton-growing areas, a prolonged ban would become a multi-resource, global game changer, involving water, land, biomass, energy, chemicals and metals. In short, one of globalization’s gifts to material efficiency is the need to include global impacts on multiple linked resources in impacts of, for example, trade flow changes.


   Whatever one thinks about current climate models, no one disputes that the global climate is an extremely
complex system to model. Of course, materials efficiency is linked to climate change and global warming, but even by itself it is a complicated subject to model on a global level. There is also the question of new methods for assessing global material efficiency, for example, in material flows. Social network analysis (SNA) (or organizational network analysis) has already been applied to global trade [53], and the promise of merging this type of network flow analysis with other material efficiency approaches carries great promise in our opinion. The technium approach, and similar precursors such as ‘manufactured capital’ [54], lends itself well to algorithmic treatment, and a combination of SNA with cladistics-related algorithms [55] would seem to offer promise.

These are but three of the areas that offer, in our opinion, great promise in combining the resource convergence concept, complexity and material efficiency.

(iii) The Resource Power Index

For a demonstration of weighing trade-offs and assessing the importance of resources in material efficiency decisions (item 1 above in §4b(ii)), we present our ReP, which has its roots in political power, pure and simple. Coalition theory in political science mostly uses game theory for a study of alliances, their rise and their fall. The Banzhaf Power Index is an index that quantifies the power of blocs in a vote with amounts of votes (e.g. number of members of parliament of a party) not necessarily equally divided. The index is named after John F. Banzhaf III, but it was originally invented by Penrose in 1946, and is also known as the Banzhaf–Coleman index. The Banzhaf index lists all winning coalitions, then analyses critical voters. Critical voters are voters who by changing their stand can reverse the end result. Power is measured as proportions of all swing votes possible. Using the Banzhaf index, the power of, for example, smaller parties between two large blocs becomes measurable—albeit in a way that does not capture all the drama of political intrigue, of course.

In our ReP algorithm, we focus on the question of who/what has the power to achieve a certain outcome of certain value. How the algorithm works is best illustrated by a hypothetical example. We could choose one on a macro-level; but, here we take a micro-level investment analysis instead of, for example, an EU political decision on a Directive. Some simplifications have been made in the reasoning to make the example more understandable. The purpose is to introduce the method as part of resource convergence thinking, not to solve an actual example in great detail.

It should be noted that, as in LCAs, the boundary problem plays a great role in ReP. That is, for a local problem, local political and opinion climates are the key in a realistic analysis of decision-making. For a global resource power comparison, the definition of politics and opinions easily becomes an oversimplification, unless one is satisfied with taking a very top-down approach ignoring global diversity.

(iv) ReP example

A mining complex in a water-critical location is faced with problems related to water pollution and consumption, metal purity and energy consumption. The resources examined are metal, water and (bio)energy. Possible outcomes are three investments: one in water purification (10 million euros), another in a bioenergy upgrade for metal processing (60 million euros), and a third in a scrubber for CO₂ (2 million euros). The question is: metal, water, energy: what is their internal power relationship in this particular case?

The calculation goes as follows:

— Resource coalition formation: there are seven possible coalitions for the three ‘issues’—metal, water, energy, metal + water, metal + energy, water + energy and metal + water + energy.

— Outcome analysis: we examine each coalition and its outcome—no investment, water purification, energy upgrade and, finally, water and energy investments.
Table 2. Resource coalitions and outcomes.

<table>
<thead>
<tr>
<th>resource coalition</th>
<th>logic</th>
<th>outcome and value</th>
</tr>
</thead>
<tbody>
<tr>
<td>metal</td>
<td>what is needed, if we look only at energy-related needs?</td>
<td>energy upgrade for metal quality, 60 million euros</td>
</tr>
<tr>
<td>water</td>
<td>what is needed, if we look only at water-related needs?</td>
<td>water purification, 10 million euros</td>
</tr>
<tr>
<td>energy</td>
<td>what is needed, if we look only at energy-related needs?</td>
<td>because we do not consider metal quality, 0 euros</td>
</tr>
<tr>
<td>metal + water</td>
<td>what is needed, if we look only at metal- and water-related needs?</td>
<td>energy upgrade for metal quality and water purification, $60 + 10 = 70$ million euros</td>
</tr>
<tr>
<td>metal + energy</td>
<td>what is needed, if we look only at metal- and energy-related needs?</td>
<td>energy upgrade for metal quality and scrubber (because we also consider energy emissions), $60 + 2 = 62$ million euros</td>
</tr>
<tr>
<td>water + energy</td>
<td>what is needed, if we look only at water- and energy-related needs?</td>
<td>water purification does not increase energy consumption to the degree that a scrubber would be needed, 10 million euros</td>
</tr>
<tr>
<td>metal + water + energy</td>
<td>what is needed, if we look only at metal-, water- and energy-related needs?</td>
<td>energy upgrade for metal quality and water purification, and scrubber $60 + 10 + 2 = 72$ million euros</td>
</tr>
</tbody>
</table>

Table 3. Resource coalitions, outcomes and critical votes.

<table>
<thead>
<tr>
<th>outcome</th>
<th>coalition</th>
<th>critical vote(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy upgrade for metal quality, 60 million euros</td>
<td>metal, metal + water, metal + energy, metal + water + energy</td>
<td>metal (all others are non-critical)</td>
</tr>
<tr>
<td>water purification, 10 million euros</td>
<td>water, metal + water, metal + water + energy</td>
<td>water (all others are non-critical)</td>
</tr>
<tr>
<td>scrubber, 2 million euros</td>
<td>metal + energy, metal + water + energy</td>
<td>metal, energy (water does not change the outcome)</td>
</tr>
</tbody>
</table>

— Critical votes: from the outcome analysis, we can isolate the critical ‘votes’. First, we tabulate who influenced what in table 2.
— ReP for this case: now, we can calculate the power index for each resource, as shown in table 3.

(v) Uses for the Resource Power Index

The ReP was created to fit the following decision-making environment:

— we have legislation and regulation that makes certain actions necessary;
— there are changing opinions on the markets/among the public that make other actions necessary in practice;
— we emphasize decisions where several ‘one-eyed’ viewpoints, i.e. viewpoints focusing on only one issue, and all combinations of such are given consideration; and
Table 4. Power index for resources.

<table>
<thead>
<tr>
<th>resource</th>
<th>critical in coalition</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>metal</td>
<td>energy upgrade: metal, metal + water, metal + energy, metal + water + energy; scrubber: metal + energy, metal + water + energy</td>
<td>60 + 60 + 60 + 60 + 2 + 2 = 244 actual million euros</td>
</tr>
<tr>
<td>water</td>
<td>water purification: water, metal + water, metal + water + energy</td>
<td>10 + 10 + 10 = 30 actual million euros</td>
</tr>
<tr>
<td>energy</td>
<td>scrubber: metal + energy, metal + water + energy</td>
<td>2 + 2 = 4 actual million euros</td>
</tr>
</tbody>
</table>

— we are dealing with decisions where the outcome of \((A + B + C)\) may be different from the sum of the outcomes of \(A, B\) and \(C\).

In itself, ReP is an integrator of viewpoints of different foci since it, as in the example above, contains all combinations of viewpoints (table 4). Thus, metal has in this case the ReP 244, water 30, energy 4, the unit being actual million euros. Recalculated so that the smallest has the value 1, we have the power ratio for metal : water : energy = 61 : 7.5 : 1. That is, the power and influence of the resource metal in this specific case on decisions is 61 times that of energy, with water being 7.5 times more influential than energy, but 61/7.5 times less influential than metal.

Possible uses include:

— decision-making from international to household level;
— quantifying resource power proportions in different parts of the world;
— quantifying the power of different regulations (use regulations as ‘voters’; what are the critical regulations in different coalitions with different outcomes?); and
— creating weighting sets for LCAs.

5. Conclusions

Material efficiency is not a panacea, but it lies at the intersection of many problems of global sustainability, be it in our complex global manufacturing ecosystem, Earth as a whole, in transnational agreements or focused investment decisions.

Reducing the usage of a single material in a value chain may require ingenuity and wide cooperation, but conceptually it is not a problem: it is known as, for example, supply chain management and belongs to everyday business practices.

When the problem stretches to several linked resources in changing circumstances, with political decisions among boundary setters, we need new concepts. We have to understand

— the nature and reach of linkages between resources (be it land, water, energy, metals, biomass, carbon) and
— the power and influence of each resource in decision-making in different settings.

In this paper, we have concisely gone from the time dimension (our ancestors were faced with the same problems) to a very, very short history of resource thinking, and then introduced our resource convergence concept. Using text mining on a sample of 22 articles, publications and patents linking different resources, we have shown in a ‘visual literature review’ how resource convergence emerges from unrelated texts. To demonstrate one new method of application under the resource convergence umbrella, we have used a case example with our method ReP.

In our opinion, mastering complexity, not oversimplifying it will be the key to solving the challenges we are facing, and mastering resource convergence and translating it into material efficiency is one of the central battlefields. At the same time, the results from this analysis of
complexity must be translated into as simple rules as possible. For resource efficiency, a suitable analogy is perhaps that of medical practice. Medicines tend to have side-effects; some medications interact badly with others, at worst like binary toxins. Medical doctors must solve the practical problems they are presented with, while minimizing the negative interconnections and trade-offs with the patient’s health. For this purpose, there are manuals enumerating the side-effects and practical know-how in databases supporting medical decision-making. Unfortunately, mistakes happen, and the evolution of medicine and the sheer amount of possible, rare interactions complicate things.

In the same fashion, creating databases and ‘manuals’ of resource interactions in different conditions, for practical applications, is an essential outcome goal. For this to happen, extensive work in both understanding the mechanisms of interaction and calculating the impacts is necessary. What we have shown in this paper is a core framework and some details of the direction we see as worth pursuing. Our work here is a step in outlining tasks along both routes, with practical examples of interaction and an algorithm for one of the many problems ahead. Our definition of resource convergence as resources, habits and processing technologies converging towards platforms that enable substitution of and new interaction with physical resources also points to the next focus. Linking resources and technology (as in a technium-like approach) and quantifying impacts are avenues we intend to concentrate on next. Building on work done in network analysis of global trade flows is, in our opinion, the central foundation.

References

14. WeTap. WeTap map. See http://wetap.wordpress.com/.