GAiA

4 | 2018

ECOLOGICAL PERSPECTIVES FOR SCIENCE AND SOCIETY
ÖKOLOGISCHE PERSPEKTIVEN FÜR WISSENSCHAFT UND GESELLSCHAFT

- KLIMASCHUTZ UND LEBENSMITTELWAHL
- SUSTAINABILITY IN DEMOCRACIES
- NACHHALTIGKEITSFORSCHUNG AN DER FH

oekom verlag

GAIA is available online at *www.ingentaconnect.com/content/oekom/gaia*
www.oekom.de | B 54649 | ISSN print 0940-5550, online 2625-5413
GAIAEA 27/4, 337–408 (2018)

Towards a Historical Understanding of Critical Raw Materials

Suggestions from a History of Technology Perspective

Does the current debate on critical raw materials have precursors in history and is there anything we can learn from it? Notably during industrialization, certain materials were considered important to further development and at the same time prone to scarcity. A history of technology perspective shows how such considerations shaped material change.

Sebastian Haumann

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GAIA 27/4 (2018): 373 – 378

Abstract

The current debate on critical raw materials lacks a historical dimension. While the idea of identifying certain raw materials as particularly problematic – and therefore critical – to future development is not a new one, a historical perspective has not yet been systematically integrated into the debate. This article explores concepts from history of technology to make suggestions about how we can better understand the ways in which reflection triggers and shapes material change. It discusses the concepts of social construction of technology (SCOT) and the development of technological systems, applying them to the debates on the criticality of wood and limestone during the age of industrialization.

Keywords

critical raw materials, history of raw materials, social construction of technology

Critical Raw Materials from a Historical Perspective

Over the past decade, the notion of "critical raw materials" has increasingly informed discussions on economic as well as environmental concerns over limited resources and on strategies proposed to cope with these limitations. Criticality is defined by the importance of a material for future development and the vulnerability of the provision with this material, which is considered a potential threat to development (EU Commission 2014, Blengini et al. 2017). Despite the fact that future change is central to these discussions, stressing the importance of temporal dynamics, a historical perspective has not yet been systematically integrated into the debate. Strikingly, the analytical concept of criticality is so far inherently ahistorical. The aim of this article is to explore the potential of concepts from history of technology to fill this gap and enhance our understanding of critical raw materials and their temporal dynamics.

Existing research that takes the history of materials into account has rightly pointed out the relevance of social reflection and narratives around raw material use. By reflecting on their use of raw materials, societies have in the past been able to shape the consumption of these materials, and continue to do so today. Therefore, narrating "substance stories", as proposed by Stefan Böschen et al. (2004), or devising multiple narratives of raw material use in the "Anthropocene" as recently suggested by Christophe Bonneuil and Jean-Baptiste Fressoz (2016), appears to be the dominant benefit of a historical perspective. According to this strand of research, discourse has an impact and therefore needs to be developed further, with critical raw materials being a case in point (Moezzi et al. 2017, Schmidt 2013). While it is easy to fall in with the argument that the value of a historical approach lies in demonstrating the long traditions of social reflection on raw material use, it is less evident why and how this reflection had, and continues to have, an impact.

In order to explore the potential of historical concepts beyond the analysis of reflection and narratives, I will turn to a strand of

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https://doi.org/10.14512/gaia.27.4.9

research in history of technology that focuses on the social construction of technology and the dynamics of technological systems. Following Sabine Höhler's (2015, p. 15) claim, this can provide insight into how "problems can be conceived of as historically and culturally constructed and yet provoke real material consequences". Originally directed against technological determinism, the concepts of social construction of technology and technological systems stress the social embeddedness of technological development (Heßler 2012). Social construction of technology, discussed in the first section of this article, focuses on the way problems are conceived and solutions are devised. In the second section I will introduce the concept of technological systems, in which social constructions are dynamically linked to material components, such as technical artifacts and raw materials. While both concepts are well established, they have only rarely been applied to raw material use and provisioning (Misa 1995, Zumbrägel 2014). In the closing section I will try to fill this gap and draw some conclusions for the current debate on critical raw materials.

Social Construction of "Criticality"

It is easy to identify instances in the past, particularly during industrialization, that display striking similarities to the current debate on critical raw materials, even though the term itself was not used. Prominently, the shortage of wood and the transition to fossil fuels have been discussed in terms that resemble central aspects of the current notion of "criticality" by contemporaries as well as by historians. However, this also holds true of less well researched materials, such as limestone, a raw material arguably as important to industrialization as fossil coal. In essence, ascribing "criticality" to certain materials is a means of problematizing raw materials that has a long history.

Taking the cue from history of technology, contention and problematization are important aspects of social construction. Criticality, therefore, is not immanent to the materials or the technologies in which they are used, but an outcome of the perception of problems and challenges. At the same time, the way problems are conceived is not without consequences as it predetermines which solutions are proposed (Pinch et al. 1984). While arguments and indicators have differed through the centuries, the essential logics of problematization have remained remarkably stable. In the following section, I will outline three recurring features of the debate according to which raw materials have been defined as particularly problematic and on which subsequent solutions have been based: future scenarios and expectations, the dualism of enabling and vulnerability, and the evaluation of value-added chains.

Critical Raw Materials within Future Scenarios – Economic Development and War in the 19th Century

On the most abstract level, critical raw materials are considered to be essential within broader future scenarios. The relevance of such scenarios for the construction of technologies, scientific knowledge and environmental policies has been stressed in recent historical research (Heymann et al. 2017, Radkau 2017, Seefried 2015). Scenarios are instrumental in generating and substantiating predictions. They also shape expectations about the technologies central to future development and, in turn, about the demand for raw materials used and consumed in these technologies. Current scenarios, focusing on the ideal of sustainable growth, suggest the importance of information and "green" technologies, in which certain raw materials are deemed to play a decisive role, such as tellurium, indium and rare earth elements (EU Commission 2014, pp. 7 f., Marschall and Holdinghausen 2018).

Placing certain materials into overarching scenarios is not new, as the debate over the so-called "wood brake" (Sombart 1928) indicates. Famously, Werner Sombart argued that a significant shortage of wood had led to a severe energy crisis at the turn of the 19th century that would have resulted in the premature "end of capitalism". Even though Sombart wrote more than 100 years afterwards, he summarized a contemporary perception. By the end of the 18th century, state bureaucrats and economic thinkers but also local administrators and entrepreneurs routinely voiced concern over the limited availability of wood. Wood was portrayed as a central raw material for the maintenance of the economic and public wellbeing in the cameralist state, in which resource use was tightly administered to increase overall wealth. This concern was further reinforced as cameralist thought slowly gave way to the liberal preoccupation with economic growth based on energy-intensive industrialization at the beginning of the 19th century (Grewe 2004, Radkau 1983).

A century later, imperial expansion and military competition were the main issues concerning the future. Important scenarios focused attention on military technologies and weapons made of steel in particular (Misa 1995). As raw materials deemed necessary for the further development of these technologies were evaluated, the use of limestone was identified as a problem. The material had been used as flux in iron smelting and steel production long before, but its relevance was reasserted in the social construction of military technologies at the turn of the 20th century (Haumann 2016). In the scenarios leading up to World War I, the quantitative and qualitative development of steel production appeared to hinge on the availability of limestone, among other materials.

The Dualism of Enabling and Vulnerability

The invocation of future scenarios and the expectations that frame the problematization of raw materials are closely linked to the dualism of enabling and vulnerability. For the social construction of technologies this dualism is essential as it highlights opportunities and at the same time indicates problems to be resolved in order to realize these opportunities. The juxtaposition of potentials on the one hand and their impediment on the other is a recurring feature of debates on raw materials (Vikström 2017). With the availability of critical raw materials it becomes possible to design technologies central to an envisaged future. A lack of these materials would threaten this development. In the current debate, "criticality" is therefore defined in relation to this dualism of enabling and vulnerability (EU Commission 2014, Blengini et al. 2017).

In 1839, the owners of the Gutehoffnungshütte iron works, which later became one of the largest industrial enterprises in the Ruhr, argued in this vein: “The increasing scarcity of wood charcoal allowed the use of our two blast furnaces only for a brief period”, and added that this threatened the economic boom on the horizon (Bergamt Essen-Werden 1839, all translations by the author). By the late 1830s, it was apparent that iron smelting was a key technology of future development as the first railway lines were projected and built. At this point in time, the charcoal availability was still presented, at least by German iron producers, such as the Gutehoffnungshütte, as the decisive factor that rendered future development vulnerable. The construction of this kind of dualism suggested that the entire future scenario of industrial growth in the 19th century was endangered.

Similarly, on its 25th anniversary in 1912, the Rheinisch-Westfälische Kalkwerke, a major provider of limestone for Germany’s iron and steel industry, put on a play in which it highlighted the relevance of the material for armament. If it wasn’t for limestone, “iron and steel would be powerless […] to help with nations’ triumphs and to win their numerous battles” (Balz 1912). While this literary document appeared as an allegory to the past, it referred to future possibilities of military technologies based on steel. At the same time, it was a warning alluding to the threat of scarcity that would weaken the national preparedness for war. In fact, this warning was widely understood by contemporaries as the potential scarcity of limestone had seriously worried iron and steel producers since the late 1880s and had become an argument in the public debate (Haumann 2016). At the beginning of the 20th century, invoking the dualism of enabling and vulnerability was a convincing way to highlight the particularly problematic character of limestone.

Thinking Along Value-Added Chains – Identifying Bottlenecks and Preconfiguring Solutions

An important reason why limestone could credibly be discussed as a problem, an idea that seems rather awkward in retrospective, was the contemporary conception of the relevant value-added chains. Currently, criticality is evaluated based on the model of value-added chains: “The importance […] of a raw material is measured by breaking down its main uses and attributing to each of them the value added of the economic sector that has this raw material as input. The breakdown […] is based on the concept of ‘value-added chains’. As each step of the value-added chain builds on previous steps, an upstream bottleneck in supply of raw material will threaten the whole value chain” (EU Commission 2010, p. 24).

Based on a very similar understanding, iron and steel producers were preoccupied with gaining control along the entire value-added chain at the turn of the 20th century. Thinking along the chain, it appeared that limestone was one of the inputs most difficult to control. Due to the legal framework in which, different from all other materials used in iron and steel production, the right to extract limestone rested with the landowner, industrialists perceived a significantly heightened supply risk for the material (Haumann 2016). Thinking in value-added chains was essential to fix indicators for criticality more precisely and to identify problematic raw materials.

In the end, neither the arms race leading to World War I was hindered by a lack of limestone nor did the “end of capitalism” materialize due to a shortage of fuel. The debate on the “wood brake” had the well-known impact of initiating the widespread substitution of wood with fossil fuels. While discussing limestone was confined to a much smaller group of people and its effects were less epochal, the debate did force the rapid expansion of limestone provision through comprehensive planning and the mechanization of quarries. From a historical perspective, it becomes clear that the problematization of these materials as “critical” was decisive. Criticality was socially constructed as it placed materials within broader future scenarios, effectively urged that action be taken through the dualism of enabling and vulnerability, and shifted the focus on defined problems along the value-added chains where change was to be pushed ahead. Following the concept of social construction of technology, these features of the problematization of critical raw materials did not only drive material change. They also formed the basis for proposed solutions discussed in the next section.

The Dynamics of Raw Material Use within Technological Systems

We have seen that the problematization of critical raw materials and its specific features are a necessary condition for social reflection to have an impact and for material change to set in. However, this does not sufficiently explain how change takes place. While social construction of technology suggests that problematization preconfigures potential solutions, the concept of technological systems offers a useful framework to analyze the subsequent technological development involving raw materials considered “critical”. In history of technology social construction and the concept of technological systems are closely related as they share the premise that technological development is socially embedded. Technological systems build on certain forms of social construction and link them to the design of artifacts, networks and materials (Heßler 2012).

Linking Social and Material Components – The Adaptation of Raw Materials into Technological Systems

Drawing on the example of electricity provision, Thomas P. Hughes (1987, p. 51) defined technological systems as combining social with material elements: “Among the components in technological systems are physical artifacts, such as turbogenerators, transformers, and transmission lines in electric light and power systems. Technological systems also include organizations, such as manufacturing firms, utility companies, and investment banks, and they incorporate components usually labeled scientific, such as books, articles, university teaching”. The components are interdependent and enmeshed to form a technological system that resembles the notion of a value-added chain from raw material extraction to consumption. Consequently, raw materials also fig-

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ure as material components. Hughes prominently states that "[b]ecause they are [...] adapted in order to function in systems, natural resources [...] also qualify as system artifacts" (Hughes 1987, p. 51).

The process of adaptation might best be described as making links between social and material components. Significantly, the use of a certain raw material is not determined by pre-given material necessities alone but depends on the relation to social components. These components, among them the organizational structure of raw material provisioning or scientific knowledge, are socially constructed. Organization and knowledge reflect contemporary assumptions, scientific practices and often also economic interests, fusing established understandings with expectations of further development (Frehner 2011, Mitchell 2011, Westermann 2014). Through the interdependencies within technological systems, they have an impact on material components. Therefore, adaptation of raw materials is – the materials' physical properties notwithstanding – to a large degree shaped by social construction.

Via the construction of social components, the problematization of raw materials as "critical" impacts on material change. The reflection on critical raw materials has been an important catalyst for processes in which expectations, scientific assumptions, but also entrepreneurial strategies, state regulation and geopolitical relationships relevant to technological systems shifted (Bösch and Graf 2014, Radkau 1983). The problematization of critical raw materials prefigured changes in the adaptation of materials by shifting the focus on defined problems described as "bottlenecks" along the value-added chain, where change was to be pushed ahead. In terms of the development of technological systems these "bottlenecks" can be understood as reverse salients: "Reverse salients are components in the system that have fallen behind or are out of phase with the others [...] in need of attention" (Hughes 1987, p. 73). Therefore, efforts to find solutions for the problems, to generate new knowledge or revise organizational structures, will increase if raw materials are identified as reverse salients.

The Dynamics of Technological Systems – Reconstructing Knowledge and Value-Added Chains

In the historical situations that set these changes to technological systems into motion, the social construction of problems and its specific features outlined in the first section of this article played a decisive role. Early attempts to cope with fuel shortage in the 18th century rested on administrative interventions to allot the supply of wood to the iron industry. Alternatively, entrepreneurs increased their efforts to enhance the energy efficiency of blast furnaces (Fremdling 1990). Even though it was in principle known, substitution with fossil coal was not a solution that appeared realistic or worth pursuing outside of Great Britain at the beginning of the 19th century because it produced iron of inferior quality. It was only when future scenarios around the creation of a railway system gained traction in the 1820s and 1830s that the question of how to fuel the energy-intensive production of iron and steel gained new momentum. This did not only heighten the sense of urgency to act upon potential fuel scarcity once more but also influenced the conception of value-added chains in a significant way. With the anticipation of a mushrooming demand for rails a new variant of the value-added chain was conceived in which iron made with fossil fuel was deemed qualitatively acceptable (Fremdling 2000). Only then did the adaptation of fossil fuel into the technological system of iron making appear as the most desirable solution, superseding the drive for the ever more efficient use of wooden fuel.

Before substitution could be widely successful, the emerging desire to make the material change sparked intensified construction of knowledge (Rasch 2015). A renewed interest in geological surveying from the 1820s through the 1840s was largely inspired by the demand to know more about coal deposits usable specifically for iron smelting. In the same period, analytical chemistry advanced through Robert Bunsen's inquiries into the chemical reactions inside British coal-fired blast furnaces. On another level, the establishment of joint stock companies and the liberalization of the mining sector proved essential social components to reassemble the technological system. None of the giant iron works using fossil coal that were being set up on the continent could have gone into operation without the creation of new knowledge and new financial opportunities.

Similarly, concerns over limestone at the turn of the 20th century were triggered by a significant shift in the value-added chain of iron and steel production. The widespread installations of basic converters from the 1880s onward changed the perception of the material, suggesting its sharply rising importance. In the basic process of steel production limestone and the closely associated dolomite became key ingredients when raw iron was converted into steel that could be used in the design of a new generation of mass-products, among them armory. Under this impression, supply risks were identified to be rooted not in the general availability of the material but in the actual access to deposits and the limited extent of possible extraction. As the right to exploit limestone rested with the landowner, dispersed property distribution only allowed small and fragmented operations. In the face of this situation, overcoming limits to the expansion of supply, not substitution, was considered the most desirable solution. To achieve this, interested companies began matching geological knowledge with information on property owners and devising organizational structures that would sustain the large-scale exploitation of limestone. On this basis it became possible to reassemble the technological system. Companies bought up large connected tracts of land on which extensive and mechanized quarries could be projected and put into operation (Haumann 2016).

Temporary Flexibility of Technological Systems – A Potential for the Novel Adaptation of Raw Materials

Despite the fact that the development paths in the two cases presented here differ considerably, they both show how the problematization of raw materials as "critical" led to temporary flexibility of technological systems. At times there is "not only [...] flexibility in how people think of, or interpret, artefacts, but also [...] flexibility in how artefacts are designed" and raw materials adapted, for that matter (Pinch and Bijker 1984, p. 421). This is what happened when wood and limestone were conceived as "critical". While in the case of wood, adaptation of a new material, the substitution by fossil coal, was the solution, in the case of limestone changes in the technological system were induced in order to expand the material's availability. However, the comparison highlights that reflecting on criticality triggered and accelerated flexibility in both technological systems, albeit at different points and in different depth.

Eventually, flexibility will diminish and lead to the closure of a technological system. Closure "involves the stabilization of an artefact and the disappearance of 'problems'" (Pinch and Bijker 1984, p. 426). In the case of raw materials this equals the lock-in on particular materials together with the stabilization of interrelated social and material components. The prevailing design of blast furnaces, the organization of mechanized quarries, company strategies and solidified knowledge reinforced the use of certain raw materials and impeded further change. The flexibility that flashes up under the impression of heightened problematization is transformed into persistent patterns of raw material use as the closure of technological systems sets in. Eventually, problems identified as "critical" will appear to be corrected, eroding the necessity for change.

Conclusions

For the systematic integration of a temporal dimension into the current debate on critical raw materials, concepts from history of technology offer a number of clues. ***First,*** it will be important to pay more attention to the social construction of "critical raw materials" as a problem. Problematization prefigures the broad course of material change. History shows that change is more often driven by social construction than by material necessity and it makes little difference whether challenges are real or anticipated. The wood shortage of the 18th and 19th century was often alluded to in an instrumental way and far from being a universal threat (Grewe 2004, Radkau 1983). The example of limestone suggests that the relevance of social construction even goes beyond this. Not only was there never a real scarcity of the material, but there was also never a price hike indicating any excess demand (Haumann 2016). Closer attention to the social construction of "criticality" suggests that the widely held assumption that the use and consumption of raw materials is regulated by material necessity or by rising costs might not be decisive. Instead, what matters are the specific features of problematization. Factors such as real material scarcity or rising costs might be embedded in these constructions, but not necessarily so. In historical perspective it appears that future scenarios, the dualism of enabling and vulnerability and the evaluation of value-added chains are more important for triggering and shaping material change.

Second, and following from these considerations, the historical perspective shows that technological systems can be pushed into a state of flexibility. Under the influence of amplified problematization, new knowledge or organizational opportunities may emerge that help to loosen existing relationships with material components, such as raw materials, and to adapt new ones. For this reason, it might indeed be worthwhile to elaborate on narratives around raw materials. Intensified social reflection, as recently suggested (Böschen et al. 2004, Bonneuil and Fressoz 2016), can contribute to the flexibility of technological systems. This opens up opportunities to replace raw materials deemed "critical" with materials that were until then considered unsuitable, uneconomical or even impossible to use, or to rearrange exploitation and provisioning systems. However, enhanced awareness and knowledge do not automatically stimulate technological change. Instead, more historical research is needed on the flexibility of raw material use.

Third, while successful material change can mean overcoming impediments, it will most likely lay the foundation for future challenges. Material change is accelerated in phases in which technological systems are flexible. The fact that change takes place does not, however, say anything about its long-term direction and sustainability. With the successful substitution of wood, for example, the iron and steel industry became one of the main consumers of coal and arguably one of the most important drivers of the general shift to fossil fuels that we deplore today (Sieferle et al. 2006, p. 131–139). This caveat is all the more important as any flexibility can eventually lead to lock-in effects that may generate new problems in the future (Brüggemeier 2014). With the current discourse on critical raw materials we appear to be standing at the next threshold in this long historical dynamic. From a historical perspective, the current debate on critical raw materials has the potential to usher in material change, for the better or the worse.

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Submitted July 13, 2018; revised version accepted November 7, 2018.

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