This is the accepted version of the following article: Nuss, P. 2016. Thanatia: The Destiny of the Earth's Mineral Resources: A Thermodynamic Cradle-to-Cradle Assessment, by A1 - Antonio Valero Capilla and A1 - Alicia Valero Delgado . Hackensack, NJ, USA: PB - World Scientific Publishing Company , 2014, 672 pp., ISBN 978-981-4273-93-0, hardcover, $158.00. Journal of Industrial Ecology: n/a-n/a, which has been published in final form at http://onlinelibrary.wiley.com/doi/10.1111/jiec.12426/abstract .

Book Review

Thanatia: The Destiny of the Earth's Mineral Resources: A Thermodynamic Cradle-to-Cradle Assessment by Antonio Valero Capilla and Alicia Valero Delgado. 2014. ISBN: 978-981-4273-93-0. 672pp. World Scientific Publishing Company: Hackensack, NJ, USA. $158.00 (hardcover).

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Antonio Valero Capilla and Alicia Valero Delgado are both well-known authors in the area of thermoeconomics – a school of heterodox economics that makes use of the laws of thermodynamics to account for the cost of natural resource use in the form of energy, entropy, or exergy, and helps to point out irreversibilities in production systems. Their latest book centers on a simple but important concept: 'Exergy replacement cost' as the exergy required given currently available technology to return a mineral resource from a completely dispersed state, termed "Thanatia", to the physical and chemical conditions currently present in nature. Exergy originates from the second law of thermodynamics and is defined as the “maximum work that can be obtained from a system when it reaches equilibrium with a reference environment (R.E.)”. The concept of replacement cost (or thermodynamic rarity) attempts to highlight the exergy bonus of today’s naturally-occurring mineral deposits and how much it would cost society (in exergy terms) to restore minerals back to their original state in nature (at typical ore grades in today’s mineral deposits). This helps to incorporate a “grave-to-cradle” perspective into mineral resource assessments.

Today’s societies with their concentration of modern technologies, low-carbon transportation and renewable energy systems, demand enormous quantities of base metals (e.g., iron, copper, aluminum) as well as nearly all of the minor or scarce metals of the Periodic Table of the Elements in order to ensure proper functioning and performance (Greenfield and Graedel 2013; Graedel and Erdmann 2012). As a result, the issue of resource scarcity and criticality has gained substantial interest in recent years (Graedel et al. 2015; EC 2014, 2010; IW Consult 2011; BGS 2012; Morley and Eatherley 2008). There is also an ongoing discussion in the area of life-cycle assessment (LCA) as to how mineral resources should be evaluated in the life-cycle impact assessment (LCIA) stage (Klinglmair et al. 2013; Mancini et al. 2013; Vadenbo et al. 2014). The use of thermodynamic indicators has so far played only a minor role in the evaluation of mineral resources. With regard to exergy, the analysis is often time-consuming and difficult to understand, and establishing a proper R.E. (Szargut 1989) for exergy evaluations of mineral resources can be difficult (Gößling-Reisemann 2008). Furthermore, when compared to fossil fuels, non-fuel minerals consistently have lower exergy values resulting in wrong conclusions with regard to their value in the system analyzed (Gößling-Reisemann 2008; Valero and Valero 2015).

The book authors propose to overcome these challenges by defining Thanatia (from the Greek word θάνατος "death") as a possible baseline environment to which currently existing mineral deposits can be compared. Thanatia is seen as a possible end to the "Anthropocene" period (Crutzen 2006) in which all concentrated materials have been extracted and dispersed throughout the crust and all fossil fuels have been combusted (Valero et al. 2011a, 2011b). The total mineral exergy of a mineral substance is then calculated as the sum of chemical exergy, concentration exergy, and comminution exergy. Only chemical exergy is calculated relative to the R.E., while both concentration and comminution exergies use Thanatia as a baseline. In contrast to traditional exergy analysis (which typically only look at one chemical substance per chemical element in the R.E. and do not account for their concentration), the approach proposed by Valero and Valero incorporates the typical mineral concentrations of a mine (i.e., today's ore deposits provided by nature) and that of the average concentration in the Earth's crust (i.e., Thanatia). This allows quantification of the 'hidden' exergy cost associated with decreasing the concentrated state of minerals in natural deposits though extraction, production, manufacture, use, and ultimate dispersion (e.g., via dissipation or landfilling). It sends a warning message that not every mineral that is being dispersed may be replaceable (because of high exergy replacement costs).

The book by Valero and Valero provides a thorough summary of the authors' pioneering work over several years[i] using exergy as a measure in resource evaluations (Valero and Valero 2013, 2015). The reader will be impressed by the breadth of the book, discussing in great detail the need for incorporating thermodynamics into resource evaluations, their idea of defining an alternative baseline environment (the Crepuscular Earth Model or Thanatia), and a thorough summary of data sources and assumptions made to obtain the energy replacement cost of important industrial minerals. Thanatia has 17 chapters – each with a brief summary at the end. The first four chapters provide justification for using exergy-based analysis in resource evaluations and explain basic thermodynamic concepts in an easy-to-understand format. Chapters 5 to 8 provide a concise summary of the geochemistry of the earth, resources of the earth, and an introduction to mining and metallurgy as well as the production of key minerals and literature estimates of associated energy requirements. These chapters discuss aspects of the traditional 'cradle-to-grave' view of today's metal production system. The chapters can be skipped by readers already familiar with the basic concepts of mineral geology and metallurgy. The third part of the book from chapter 9 to 13 represents the core of the book. Here the details of exergy accounting and the design of the Crepuscular Earth Model (Thanatia) are described. The chapters are based on numerous scientific publication published by the authors in recent years (e.g., (Valero and Valero 2013; Valero et al. 2011b, 2011a; Valero and Valero 2015; Valero et al. 2015)). Finally, chapters 14 to 17 provide reflections on the challenges of resource depletion and discuss options to slow resource depletion (e.g., via recycling and resource efficiency measures).

Thanatia is a 'timely' book that contributes new ideas to the debate on how to quantify resource depletion. It is thereby relevant to researchers working in the field of sustainable resource management and resource criticality. It points out some of the "weak-points" of current assessment methods focusing solely on a "cradle-to-grave" system boundary, thereby not accounting for the cost of irreversibly losing substances via means of dissipation and ultimate disposal. The book also communicates interesting ideas on using exergy as an alternative for allocation in LCA (Valero et al. 2015). In my view, some of the data reported on the exergy and exergy replacement cost of several important industrial minerals could, in a next step, be incorporated into preliminary LCIA methods or increasingly combined with results from criticality studies published elsewhere (Graedel et al. 2015; EC 2010, 2014; IW Consult 2011; BGS 2012; Morley and Eatherley 2008). This would also make the material available to a wider audience. However, the book is unfortunately also written dense in repetitions and contains lengthy explanations of the thermodynamic concepts used. This makes it difficult to read at times and does not always help to 'demystify' the concept of exergy (a stated goal of the authors). Incorporating more figures to visualize the concepts use and explanations with the existing figures and graphics provided would make the book more accessible and less tedious to read.

Overall, this is a valuable collection of papers and supplemental information of the authors over the last years leading to the model of Thanatia. It is a practical, refreshing complement to the growing number of academic papers on the topic of mineral resources that will help to highlight the importance of thermodynamic concepts in natural resource evaluations.

REFERENCES

BGS. 2012. *Risk list 2012: An updated supply risk index for chemical elements or element groups which are of economic value*. Nottingham, United Kingdom: British Geological Survey.

Crutzen, P.J. 2006. The "Anthropocene." In *Earth System Science in the Anthropocene*, ed. by Professor Dr Eckart Ehlers and Dr Thomas Krafft, 13–18. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/3-540-26590-2_3. Accessed August 14, 2015.

EC. 2010. *Critical raw materials for the EU*. Report of the Ad-hoc Working Group on defining critical raw materials. Brussels, Belgium: European Commission (EC). http://ec.europa.eu/enterprise/policies/rawmaterials/ documents/index_en.htm. Accessed December 27, 2012.

EC. 2014. *Report on Critical Raw Materials for the EU*. Report of the Ad-hoc Working Group on defining critical raw materials. Brussels, Belgium: European Commission (EC). http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/crm-report-on-critical-raw-materials_en.pdf. Accessed June 10, 2014.

Gößling-Reisemann, S. 2008. What Is Resource Consumption and How Can It Be Measured? *Journal of Industrial Ecology* 12(1): 10–25.

Graedel, T.E. and L. Erdmann. 2012. Will metal scarcity impede routine industrial use? *MRS Bulletin* 37(4): 325–331.

Graedel, T.E., E.M. Harper, N.T. Nassar, P. Nuss, and B.K. Reck. 2015. Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences* 112(14): 4257–4262.

Greenfield, A. and T.E. Graedel. 2013. The omnivorous diet of modern technology. *Resources, Conservation and Recycling* 74: 1–7.

IW Consult. 2011. *Rohstoffsituation Bayern - keine Zukunft ohne Rohstoffe: Strategien und Handlungsoptionen (Raw materials situtation in Bavaria - no future without raw materials: strategies and opportunities of action)*. IW Consult GmbH Köln. http://www.rohstoffstrategie-bayern.de/fileadmin/user_upload/rohstoffstrategie/dokumente/vbw_Studie_Rohstoffe_Bayern_web.pdf. Accessed September 17, 2013.

Klinglmair, M., S. Sala, and M. Brandão. 2013. Assessing resource depletion in LCA: a review of methods and methodological issues. *The International Journal of Life Cycle Assessment*: 1–13.

Mancini, L., C. De Camillis, and D. Pennington. 2013. *Security of supply and scarcity of raw materials*. Luxembourg: Publications Office of the European Union. http://bookshop.europa.eu/en/security-of-supply-and-scarcity-of-raw-materials-pbLBNA26086/.

Morley, N. and D. Eatherley. 2008. *Material Security: Ensuring resource availability for the UK economy*. Chester, UK: Oakdene Hollins, Ltd. http://www.oakdenehollins.co.uk/pdf/material_security.pdf. Accessed September 17, 2013.

Szargut, J. 1989. Chemical exergies of the elements. *Applied Energy* 32(4): 269–286.

Vadenbo, C., J. Rørbech, M. Haupt, and R. Frischknecht. 2014. Abiotic resources: new impact assessment approaches in view of resource efficiency and resource criticality—55th Discussion Forum on Life Cycle Assessment, Zurich, Switzerland, April 11, 2014. *The International Journal of Life Cycle Assessment* 19(10): 1686–1692.

Valero, A., A. Agudelo, and A. Valero. 2011a. The crepuscular planet. A model for the exhausted atmosphere and hydrosphere. *Energy* 36(6). ECOS 2009: 3745–3753.

Valero, A., A. Domínguez, and A. Valero. 2015. Exergy cost allocation of by-products in the mining and metallurgical industry. *Resources, Conservation and Recycling* 102: 128–142.

Valero, A. and A. Valero. 2013. From Grave to Cradle. *Journal of Industrial Ecology* 17(1): 43–52.

Valero, A. and A. Valero. 2015. Thermodynamic Rarity and the Loss of Mineral Wealth. *Energies* 8(2): 821–836.

Valero, A., A. Valero, and J.B. Gómez. 2011b. The crepuscular planet. A model for the exhausted continental crust. *Energy* 36(1): 694–707.

[i] A summary of related literature is also available from the Exergoecology portal at http://www.exergoecology.com