



Universiteit
Leiden
The Netherlands

Materials and energy : a story of linkages

Kleijn, E.G.M.

Citation

Kleijn, E. G. M. (2012, September 5). *Materials and energy : a story of linkages*. Retrieved from <https://hdl.handle.net/1887/19740>

Version: Not Applicable (or Unknown)

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/19740>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/19740> holds various files of this Leiden University dissertation.

Author: Kleijn, René

Title: Materials and energy : a story of linkages

Date: 2012-09-05

Materials and energy: a story of linkages

Colophon

Materials and energy: a story of linkages

Material requirements of new energy technologies, resource scarcity, and
interconnected material flows

PhD Thesis Leiden University, The Netherlands

kleijn@cml.leidenuniv.nl

ISBN 978-90-9026938-2

Cover: Photos © Reuters

Printed by: MullerVisual

© 2012 by René Kleijn, except for the Chapters 3 to 6. Copyright of these chapters
belong to the publishers as noted at the beginning of each chapter.

Materials and energy: a story of linkages

Material requirements of new energy technologies,
resource scarcity, and interconnected material flows

PROEFSCHRIFT

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van de Rector Magnificus prof. mr. P.F. van der Heijden,
volgens besluit van het College voor Promoties
te verdedigen op woensdag 5 september 2012
klokke 11.15 uur

door

Engelbertus Gerardus Maria Kleijn

geboren te Naaldwijk in 1964

Promotiecommissie

Promotor: Prof. dr. G.J. Kramer

Co-promotor: Dr. E. van der Voet

Overige leden: Prof. dr. T.E. Graedel (Yale University, New Haven, USA)
Prof. dr. A. Tukker (Norwegian University of Science and
Technology, Trondheim, Norway)
Prof. dr. E. Worrell (Universiteit Utrecht, Utrecht)

Table of content

1	General introduction	9
1.1	The importance of the material basis of society	9
1.2	The debate on scarcity in recent history	11
1.3	Metal requirements of the energy transition	12
1.4	Relation of metal scarcity to other issues	13
1.5	Methods and tools for analysing the complex interactions between material flows	14
1.6	Aim, scope and contents	15
2	A short history of the importance of metals for humanity and the debate on their scarcity	19
2.1	The importance and scarcity of metals pre-1740	20
2.2	Metals and wood: interlinked until 1740	24
2.3	The industrial revolution, conservationism and resource economics (1740-1930)	24
2.4	World War II and the take-off of consumerism (1930-1970)	26
2.5	Environmentalism, the oil crisis and the framing of sustainability (1960-1980)	28
2.6	Dematerialization in the OECD and the metals boom (1980-2011)	33
3	Resource constraints in a hydrogen economy based on renewable energy sources: an exploration	39
3.1	Introduction	39
3.2	Core assumptions in the case study	40
3.2.1	Base year & scenario	41
3.2.2	Renewables only	41
3.2.3	Large scale biomass not included	42
3.2.4	Wind and solar provide 95% of energy	43
3.2.5	Hydrogen and electricity as carriers	43
3.3	System specification	44
3.3.1	Collection and concentration	46
3.3.2	Hydrogen production	46
3.3.3	Transmission	47
3.3.4	End use	48

3.4	Identification of possible resource constraints	49
3.4.1	Resource constraints related to energy collection	49
3.4.2	Resource constraints related to hydrogen production	53
3.4.3	Resource constraints related to transmission	55
3.4.4	Resource constraints related to end use: fuel cells & electric motors	58
3.5	Conclusions and discussion	60
4	Metal requirements of low-carbon power generation	67
4.1	Introduction	67
4.1.1	Material requirements of power generation	68
4.1.2	Goal of the study	68
4.1.3	Other constraints for low-carbon power generation	69
4.2	Analysis of CO ₂ emissions and metal requirements of different technologies	70
4.3	Implications for mass deployment - three cases	70
4.4	Methods & data sources	72
4.5	Results	75
4.5.1	Analysis of the CO ₂ emissions and metal requirements of individual technologies	75
4.5.2	Analysis of the CO ₂ emissions and metal requirements at world scale implementation - the three cases	78
4.6	Conclusions and discussion	80
5	Metal scarcity: imminent threat, eternal problem or red herring, the current debate in historical context	87
5.1	Introduction	88
5.2	Trends in demand for metals	89
5.2.1	Trends in mineral demand	89
5.2.2	Rapid growth in global material needs for infrastructure	92
5.2.3	Trends in the material complexity of products	93
5.2.4	The material needs of the energy transition	95
5.2.5	Implications for future metals demand	95
5.3	Reserves and resources, underground and above-ground	97
5.3.1	Reserves and resources, underground	97
5.3.2	Reserves and resources, above-ground	99

5.4	Trends in mineral supply	100
5.4.1	Developments in the mining sector	101
5.4.2	Globalization	102
5.5	Possible solutions for metal scarcity	102
5.5.1	Elemental and resource substitution	103
5.5.2	Functional substitution and dematerialization	105
5.6	Conclusions, recommendations, discussion & research agenda	107
6	The need for combining IEA and IE tools: The potential effects of a global ban on PVC on climate change	115
6.1	Introduction	115
6.2	The PVC and chlorine debate	118
6.3	IEA and IE tools	119
6.3.1	Integrated Environmental Assessment tools	119
6.3.2	Industrial Ecology tools	121
6.4	Application of IEA and IE tools on the case of PVC	123
6.4.1	Application of IMAGE on the case of PVC	124
6.4.2	Application of RAINS on the case of PVC	125
6.4.3	Application of LCA on the case of PVC	125
6.4.4	Application of SFA on the case of PVC	128
6.4.5	Need for a broader perspective	132
6.5	Application of a broader systems perspective	132
6.6	Discussion and conclusions	138
7	Overarching conclusions, general discussion and research agenda	143
7.1	Conclusions on the history of metal use and scarcity	143
7.2	Conclusions on the future of metal use and scarcity	144
7.3	Conclusions on methodology	146
7.4	General discussion	147
7.5	Research agenda	150
	Summary	155
	Samenvatting	163
	Curriculum Vitae	173

