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Towards zero waste production in the minerals and metals sector

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Abstract

The production of mineral and metal commodities results in large quantities of wastes (solid, liquid and gaseous) at each stage of value-adding – from mining to manufacturing. Waste production (both consumer and non-consumer) is a major contributor to environmental degradation. Approaches to waste management in the minerals industry are largely 'after the event'. These have moved progressively from foul-and-flee to dilute-and-disperse to end end-of-pipe treatments. There is now a need to move to approaches which aim to reduce or eliminate waste production at source. Modern waste management strategies include the application of cleaner production principles, the use of wastes as raw materials, the re-engineering of process flowsheets to minimise waste production, and use of industrial symbioses through industrial ecology to convert wastes into useful by-products. This paper examines how these can be adopted by the minerals industry, with some recent examples. The financial, technical, systemic and regulatory drivers and barriers are also examined.

Introduction

Many of the goods and services needed by society depend on the exploitation of non-renewable resources and renewable resources that are under threat of destruction. There is a wide consensus that the key indicators of the health of the natural environment are in decline. The United Nations millennium ecosystem assessment report of 2005 [1] concluded that approximately 60% of the ecosystem services examined in that study are being degraded. These include fresh water, fisheries, air and water purification, and the regulation of regional and local climate, natural hazards, and pests.

One aspect of the degradation of the environment is the potential depletion of natural resources. Another is the ability of the environment to cope with the impact of the emissions and wastes caused by meeting the ever-increasing material and energy needs of society. For example, in the United States more than 21 billion tonnes of resources of all kinds are consumed every year – about 80 tonnes per person per year, consisting of 76 tonnes of non-renewable resources and 4 tonnes of biomass [2]. Only 19 tonnes of these resources are used as direct inputs to processing; the rest is waste. Further quantities of wastes are produced during processing of the direct inputs and during the use and ultimate recycling or disposal of the products made from them. Other developed countries have similar patterns of consumption. The per capita consumption of materials in the European Union in the latter half of the 1990s, for example, was 49 tonnes per year [3].

This paper considers possible responses to the challenges posed by wastes from the mining and mineral processing industry.

Wastes and the waste hierarchy

A waste is commonly considered to be a thing or substance that has been discarded, or which will be discarded, and eventually sent to landfill or other disposal site. This, however, fails to recognise the possibility of it being useful again. Thus a better definition is: Something is a waste when it has no present use.

Waste reduction and elimination are not new concepts and many strategies for them have long been known. Our ancestors rarely wasted anything. Many products were remanufactured or reused and materials were recycled before being ultimately discarded. The present attitude towards wastes largely resulted from the increasing availability of cheap energy and materials following the industrial revolution. There has been a renewed focus on wastes only since the ever-increasing quantities of waste from energy and materials production and consumption began to have wide-scale environmental impacts, in the latter half of the 20th century.

The conventional waste hierarchy, reduce, reuse, recycle (the three Rs) lists waste management strategies in decreasing order of desirability. Thus, the most desirable strategy is to reduce the quantity of materials and wastes associated with a product, and to use fewer products. The next most desirable strategy is to reuse a product, and only as a last resort recycle the materials comprising the product. They focus on the reduction or minimisation of waste rather than on the elimination of wastes, and seem to have been developed with manufactured products, building and construction products, and domestic waste in mind. Their focus is on things that have had a useful life rather than on things or by-products that have not had a previous use, such as mining and processing wastes.

The focus on minimising waste started shifting towards eliminating wastes at source as a result of the European Union Council Directive 91/156/EEC of 1991 which established the hierarchy: waste prevention; recovery; safe disposal. Importantly, it addressed things that have had a useful life and by-products, such as mining and processing wastes, that have had no previous use. After several revisions, Directive 2008/98/EC of 2008 established the following hierarchy:

- prevention;
- preparation for reuse;
- recycling;
- other recovery (e.g. energy recovery);
- disposal.

Directive 2008/98/EC excludes wastes resulting from the prospecting, extraction, treatment and storage of mineral resources and the working of quarries, which had been included in earlier versions, since these are now covered specifically by Directive 2006/21/ EC which follows a similar hierarchy.

Strategies for minimising and eliminating wastes

Strategies for minimising and eliminating wastes in the production of mineral and metal commodities can usefully be grouped as follows:

- cleaner production;
- use of waste as raw materials;
- waste reduction through process re-engineering;
- industrial ecology.

These are arranged in order of increasing capacity to minimise or eliminate wastes, and hence form a hierarchy. This order also correlates with increasing degree of integration into the business of a company and the economy at large. Thus, cleaner production can be implemented at a single operation, whereas industrial ecology requires integration across companies and across industry sectors. These strategies are not mutually exclusive alternatives. There is considerable overlap between them and several strategies may be pursued in parallel.

Figure 1 illustrates the historical trend in approaches to addressing the environmental impact of wastes. Company behaviour has moved in recent decades from complying with regulations to corporate social responsibility and now needs to move to an industrial ecology approach. The drivers for this change have moved from being exclusively profit to include regulations and stakeholders. In parallel, the materials cycle focus has shifted from a focus on products only to by-products as well as products. It now needs to shift to the entire materials cycle and, ultimately, to the entire economy.

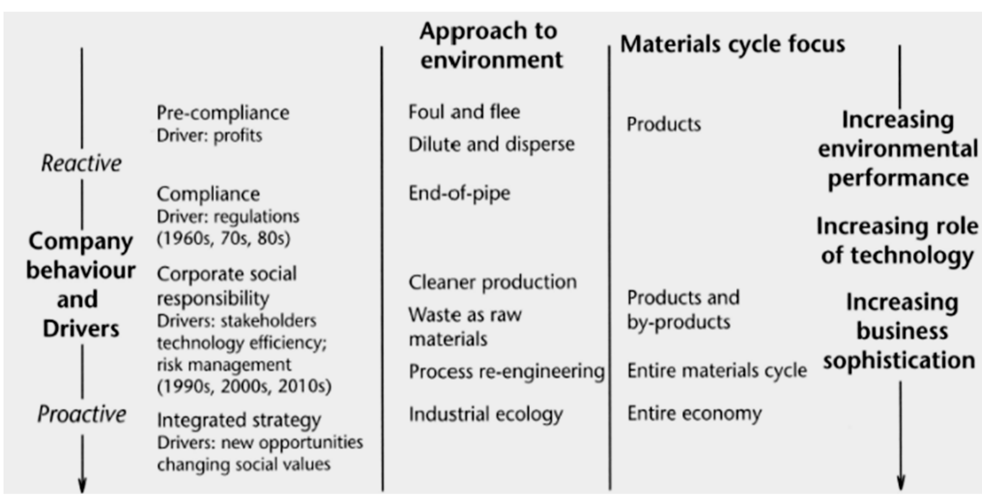

Figure 1. Historical trend in the approaches to the environmental impact of wastes (based on a figure by Giurco and Petrie [4]; with modifications).

Cleaner production

Cleaner production, also sometimes called pollution prevention, is the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment [5]. Cleaner production can be applied to the processes used in any industry, to the products themselves and to various services provided in society. For production processes, cleaner production involves one or a combination of the following:

- conserving raw materials, water and energy;
- eliminating toxic and dangerous raw materials;
- reducing the quantity and toxicity of emissions and wastes at source during the production process.

Waste is considered as a product with negative economic value. Each action to reduce consumption of raw materials and energy, and prevent or reduce generation of waste, can increase productivity and bring financial benefits to an enterprise. The similarities between eco-efficiency and clearer production are numerous. Eco-efficiency includes cleaner production concepts and captures the idea of reducing waste through process change rather than end-of-pipe approaches. Like cleaner production, eco-efficiency goes beyond pollution reduction by emphasising value creation for the business and society at large.

The key difference between pollution control and cleaner production is that pollution control is an after-the-event, react-and-treat approach while cleaner production looks forward and attempts to anticipate and prevent. Cleaner production aims to minimise or avoid practices such as waste treatment (including stabilisation, encapsulation and detoxification), waste dilution to comply with regulations (e.g. releasing contaminated water into rivers or streams during high flow periods, blending arsenic-containing fumes with flotation tailings), and transferring hazardous or toxic substances from one medium to another (e.g. wet-scrubbing gases then disposing of the contaminants as waste water). Implementation of cleaner production requires a structured, holistic, common-sense approach using systems and people to both reduce environmental impact and improve the overall company performance [6].

Wastes as raw materials

Although processing of wastes could be considered an end-of-pipe environmental solution and therefore not particularly innovative, this is far from the truth. Many of the by-products from producing mineral and metal commodities, which are now considered wastes, contain much of value. Technologies for extracting that value are often technically sophisticated. There are several incentives for considering mining and processing waste as a raw material.

- A mining and processing waste is essentially ‘free’ (since it has already been mined) and is often in a form suitable for further processing (since it may have been crushed and ground).

- Use of a waste reduces the demand for new mined material since the product produced replaces product that would otherwise have to be mined.
- Use of a waste to make a saleable product reduces the volume of waste that must be stored or disposed of. This saves on storage and disposal costs and could lead to a reduction in the environmental impact. This is particularly advantageous for large-volume wastes such as beneficiation tailings.
- Producing a saleable product adds another source of income for a company.

Use of mining and processing wastes as raw materials is not a new concept and some wastes from mining and processing are already treated to produce saleable products. Sulfur dioxide in smelter gases is routinely used to make sulfuric acid. Slags from iron and steel production are used for making aggregate materials and as a raw material in cement manufacturing. However, mining and processing wastes are a largely untapped resource and there are many potential applications. An advance would be to optimise processes so that all output streams are useful products, rather than optimising processes around the principal product. In this way, all outputs would be optimised (in terms of composition and morphology) to maximise their effectiveness as inputs for further value-adding or, as a last resort, for disposal.

While utilisation rather than disposal of mining and processing wastes is preferable, it must be recognised that not all, or even most, mining-related wastes can be used productively. The quantities of mining wastes are so large that there are insufficient bulk applications, even in construction projects, to use significant quantities. This is particularly so for rock waste and overburden from mining. Furthermore, many mines are located in remote and/or sparsely populated areas and the transportation of low-value construction products (sand, aggregate) to populated areas for use in infrastructure projects is uneconomic. Hence, the focus is necessarily on wastes from mines and processing operations close to populated areas and/or on higher-value products which can be transported economically over long distances.

Some examples to illustrate the possibilities include utilisation of red mud from Bayer processing [7,8], spent pot lining from aluminium smelting [9], fly ash from power generation, slags from smelting operations and the use of wastes in geopolymer concrete [10]. There are many other examples in the literature.

<u>Process re-engineering</u>

The strategy of waste reduction through re-engineering aims to minimise the quantity of waste produced or to produce a by-product in a form that can be used more readily. This involves some process modification; often it may be necessary to completely redesign the flowsheet. There are three broad approaches:

- flowsheet simplification;
- use of novel equipment;
- use of novel processing conditions.

Flowsheet simplification involves the removal or combination of stages to reduce the overall number of stages required to produce a mineral or metal commodity. This reduces the amount of transport, handling and physical processing of material and can potentially reduce the amount of chemical processing. This saves energy (CO_2 emissions) and reduces the quantities of other wastes. The use of novel reactors or other equipment involves utilising unique characteristics of a reactor or other item of equipment to do something that was previously not possible, or was very difficult to do. The use of novel processing conditions involves utilising relatively standard reactors and flowsheet configurations with different reagents or processing conditions, such as temperature, pressure or concentration. While one of these approaches often predominates, a technological development usually combines aspects of two or all three. Some examples are listed in Table 1.

Table 1. Some examples of processes which reduce waste production and/or energy consumption.

Flowsheet simplification	Use of novel equipment	Use of novel processing conditions
Heap leaching	Ore sorting [11]	Electrolytic production of iron [12-14]
Finex; HIsmelt iron-making processes	Underground and in-pit pre-concentration [15]	The top gas recycling blast furnace (ULCOS program) [16]
TiRO™ process for Ti metal production [17]	Castrip™ process for thin strip casting of steel [18]	Use of biomass as fuel and reductant in metallurgical processes [19]
	Dry granulation of slag, with heat recovery [20,21]	
	Solar production of aluminium and other metals [22-26]	

Industrial ecology

The term industrial ecology refers to an industrial system that operates much like a natural ecosystem in which materials circulate continuously in a complex web of interactions. While ecosystems produce some wastes (substances that are not recycled), such as fossil fuels and limestone and phosphate deposits, they are largely self-contained and self-sustaining through the constant input of energy from the Sun. In a similar fashion, industrial ecology involves focusing less on the impacts of each industrial activity in isolation and more on the overall impact of all such activities. This means recognising that the industrial system consists of much more than separate stages of extraction, manufacture and disposal, and that the stages are linked across time, distance and economic sectors [27].

The concept of industrial ecology can be understood by considering the simple models of industrial systems in Figure 2. Figure 2(a) shows the familiar flow-through, or open loop, system. Industry takes in new materials and processes them using energy, and generates products and wastes. Both the products and the wastes are external to the boundary of the system. They are considered as externalities and their impacts are borne largely by society as a whole. New materials and energy come from outside the system and the impacts of their production are borne largely outside it. Some recycling may take place through recycling end-of-life products into the manufacturing system.

Figure 2(b) shows an industrial ecosystem. This is not quite a closed loop. New materials and energy still come from outside the system and some wastes still leave it, but products and process wastes remain within the system. Responsibility for products and for process wastes, and for the impacts of their use, is borne within the system. The unusable wastes which leave the system are of three main types:

- wastes generated during the extraction of new materials (e.g. overburden and waste rock from mining);
- wastes that escape from the recycling loop (since there are losses inherent in recovering and recycling materials);
- wastes lost through the use of products (e.g. by being discarded to landfill or incinerated).

Products that are currently in use or being held for recycling, and industrial wastes and other materials which will be reused at some time, constitute a reservoir (or stock) of materials available for use in the future.

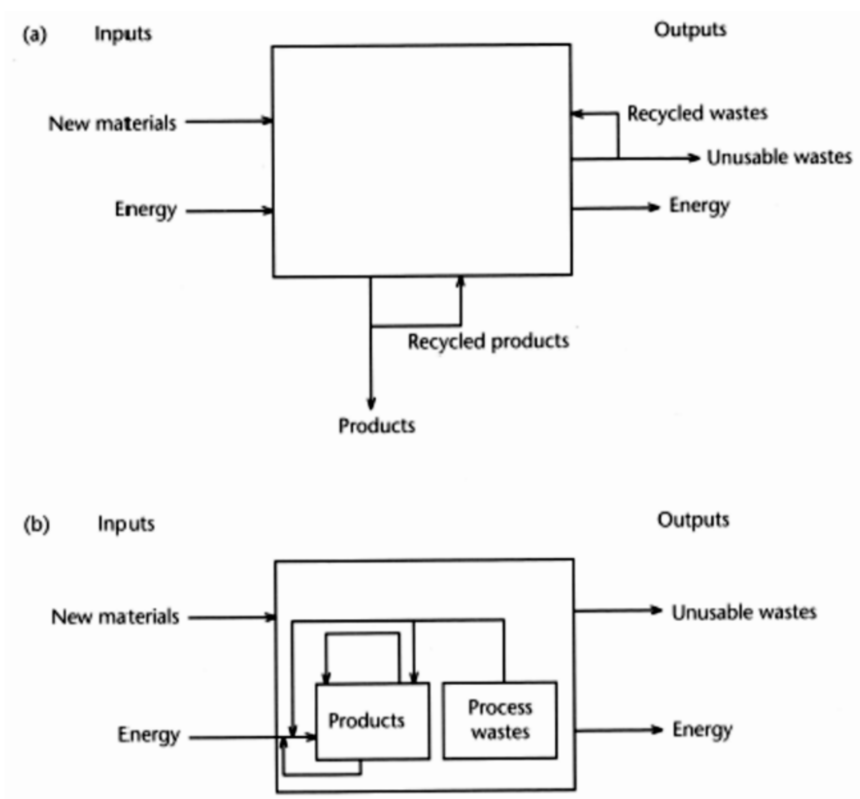

Figure 2. Open and closed material flow systems [27].

The cascading use of energy, which involves using the residual energy in liquids or steam emanating from one process to provide heating, cooling or pressure for another process, and the use of industrial by-products as feedstocks for processes other than the ones that created them, are major characteristics of industrial ecosystems.

There are many eco-industrial parks around the world and they are rapidly growing in number and complexity. Kalundborg (Denmark), Humberside (United Kingdom), Moerdijk and Rotterdam (the Netherlands) and Kwinana (Australia) are frequently cited examples [28]. Kalundborg, is the location of a highly evolved eco-industrial park [29] and is probably the best known example of the implementation of industrial ecology principles. The Kwinana Industrial Area (KIA) in south-western Australia is an eco-industrial park based largely on resource processing and is in a region which combines major resource processing operations with manufacturing, agriculture, aquaculture and recreational activities. The existing regional synergies are arguably more diverse and significant than those reported for other heavily industrialised areas [30]. Forty-seven regional synergies have been identified. Thirty-two of these are by-product synergies and 15 involve shared use of utilities. These initially developed in a largely unplanned way in response to perceived business opportunities and environmental and resource efficiency considerations. A more coordinated approach to identifying and developing linkages was adopted with the formation in 1991 of the Kwinana Industries Council.

Barriers and drivers to reducing and eliminating wastes

Very large financial investments are needed in the minerals sector for major changes in technologies. Established technologies have been refined over many years and operations usually give financial returns long after the capital costs have been depreciated. Introduction of new technologies introduces production risks which can, and often do, prove very costly. Minerals companies are reluctant to introduce new technologies unless it can be done in an incremental way with minimum risk to overall production. Furthermore, the relatively low cost of disposal of mining and mineral processing wastes in most mineral resource rich countries is a disincentive to do anything other than discard them.

Frequently, technical solutions are available or can be developed and implemented, but are too costly, risky or difficult to implement for systemic, organisational or regulatory reasons. There are no shortages of ideas and possible approaches even for radically new technologies, many of which would, if pursued, lead to more efficient or cleaner processes. But developing the right technology at the right time and in such a way that it can be introduced with minimum risk to production has proved a challenge for both technologists and business strategists in the minerals industry.

There is a large degree of entwinement between minerals companies and other industry sectors such as power generation, infrastructure (roads, rail, ports) and suppliers of reagents and other consumables. Technological changes in one area have implications that flow through the entire system. The co-production of multiple products (due to the complex nature of many mineral deposits), and the need to sell these to different markets with differing and changing demand cycles, adds another layer of complication. The range of solid, liquid and gaseous wastes produced and the technologies for managing them is another complication. These combine to make mineral and metal production companies technologically complex and this constrains the changes that can be made easily, cheaply and with little risk.

Companies often perceive themselves as in the business of making a particular commodity, such as steel or aluminium or copper. All other materials created in making their product are seen as wastes to be disposed of as cheaply as possible. Changing the culture of a company so that it perceives the resource in its entirety, not just part of it, as its greatest asset is a challenge which no minerals company has yet come near to tackling.

In most jurisdictions, regulations fail to promote closed loop systems and may actually discourage or prevent it. Of particular concern are regulations relating to the use of wastes or by-products as substitutes for virgin materials, and the assignment of liabilities. In many countries, defining a material as a waste or secondary raw material has consequences for what uses are permitted, what administrative procedures apply to its transport, export and processing, and what costs will be incurred. In some jurisdictions, a company that sells material classified as waste remains liable for any damages that may result from its use, even if it has been reused several times before the damage occurs.

Governments can help companies overcome market failure barriers by creating an environment that encourages adoption of cleaner production principles and that facilitates formation of industrial synergies, for example by:

- developing more appropriate regulations concerning wastes;
- entering into voluntary agreements with companies or industry associations on targets to achieve;
- applying market-based financial instruments such as tax concessions, taxes on emissions, emissions trading schemes and special purpose grants.

Historically, governments have responded to community expectations for better environmental outcomes through regulatory responses. The regulatory approach often prescribes conditions for resource access and use. Mining regulations often specify the maximum allowable level of pollution, minimum requirements for mine-site rehabilitation and the type of management processes that should be used to reduce environmental damage. However, in many situations the regulatory approach has failed to achieve the goals or has proved very expensive.

Market-based instruments (MBIs) for environmental management are increasingly being used for the management of natural resources and the environment. MBIs encourage behaviour through market signals rather than through explicit directives [31]. MBIs have been used successfully to control NOx and SOx emissions in the United States. They are appropriate where regulatory approaches have failed to stop ongoing degradation or where the cost is prohibitive. The focus in applying MBIs is on achieving outcomes through the self-interest of companies and individuals. MBIs have two potential financial advantages over more traditional instruments [32]. They allow different companies to make different adjustments in response to their unique business structures and opportunities; and they provide companies with an incentive to discover cheaper ways to achieve outcomes.

Concluding comments

The environmental challenges posed by non-renewable mineral resource extraction and use need to be addressed within the broader context of sustainability through an integrated strategy for managing the stocks of resources from which materials are obtained, the materials themselves, and the goods, products and infrastructure that contain materials [33].

Understanding within some industry sectors of this challenge, the need to transition to sustainability and the role of industry in this is growing, but much activity remains at the level of rhetoric. *Vision 2050* [34], developed by the World Business Council for Sustainable Development, represents a major step forward. It envisages by 2050 ‘a planet of around nine billion people, all living well – with enough food, clean water, sanitation, shelter, mobility, education and health to make for wellness – within the limits of what this small, fragile planet can supply and renew, every day’. The proposed pathway to achieve this vision involves fundamental changes in governance structures, economic frameworks, and business and human behaviour. It involves incorporating the cost of externalities (carbon, ecosystem services, water), halving carbon emissions worldwide (based on 2005 levels), and achieving a four- to 10-fold improvement in the use of resources and materials.

The minerals industry, through it’s sustainability peak body the International Council on Mining and Metals has adopted many of the principles of sustainability and corporate social responsibility but is yet to fully incorporate sustainability thinking within its business models at all levels. The inevitable closing of the materials cycle and transition to sustainability will create new opportunities for companies prepared to adopt new business models. Minerals companies can help the transition to sustainability by working proactively with their stakeholders, particularly government and government agencies, non-governmental organisations and other business sectors, to implement zero waste strategies.

References

1. *Millennium ecosystem assessment, synthesis report: ecosystems and human well-being: general synthesis* (Washington DC: Island Press, 2005).
2. A.S. Adriaanse, Bringezu, A. Hammond, E. Rodenburg, D. Rogich and H. Schutz: *Resource Flows: The Material Basis of Industrial Economies* (Washington, DC: World Resources Institute, 1997).
3. S. Moll, S. Bringezu and H. Schutz, *Resource Use in European Countries* (Wuppertal, Germany: Wuppertal Institute, 2005).
4. D. Giurco and J.G. Petrie, “Strategies for reducing the carbon footprint of copper: new technologies, more recycling or demand management? *Minerals Engineering*, vol. 20 (2007), 842.

5. *Understanding cleaner production* (UNEP, 2010); www.unep.fr/scp/cp/understanding, 2010
6. *Cleaner production* (Canberra, Australia: Department of Environment and Heritage, Commonwealth of Australia, June 2000).
7. D. Cooling, "Improving the sustainability of residue management practices – Alcoa World Alumina Australia", In *Paste* (eds A Fourie and RJ Newell) (Perth, Australia: Australian Centre for Geomechanics, 2007), 3.
8. S. Jahanshahi, W.J. Bruckard and M.A. Somerville, *"Towards zero waste and sustainable resource processing"*, In *International Conference on Processing and Disposal of Mineral and Industry Waste (PDMIW'07)*, Falmouth, UK, 14-15 June 2007, 1.
9. K. Mansfield, G. Swayn and J. Harpley, "The spent pot lining treatment and fluoride recycling project". In *Green Processing 2002*, (Carlton, VIC, Australia: Australasian Institute of Mining and Metallurgy, 2002), 307.
10. J. Davidovits, *Geopolymer Chemistry and Applications*, 2nd ed. (Saint-Quentin, France: Geopolymer Institute, 2008).
11. N.G. Cutmore and J.E. Eberhardt, "The future of ore sorting in sustainable processing", In *Green Processing 2006* (Carlton, VIC, Australia: Australasian Institute of Mining and Metallurgy, 2006), 287.
12. D.R. Sadoway, "Electrochemical processing in molten salts: from green metals extraction to lunar colonization", *Sixth International Conference on Molten Slags, Fluxes and Salts*, Stockholm and Helsinki, 12-17 June, 2000.
13. A. Cox and D.J. Fray, "Electrolytic reduction of ferric oxide to yield iron and oxygen". In *Energy Technology Perspectives*, (eds G. Reddy, C.K. Belt and E.E. Vidal), (Warrendale, PA: Minerals, Metals and Materials Society, 2009), 77.
14. Y.Y. Xiao and D.J. Fray, "Molten salt electrolysis for sustainable metals extraction and materials processing – a review", *Molten salt electrolysis: Theory, Types and Applications*, (Eds. S. Kuai and J. Meng), (NY, New York: Nova Science Publishers, 2010), 255.
15. A.S. Bamber, B. Klein, R.C. and M.J. Scoble, "Integrated mining, processing and waste disposal systems for reduced energy and operating costs at Xstrata Nickel's Sudbury operations", *Mining Technology*, vol. 117 (3), (2008), 142
16. ULCOS, www.ulcos.org/en/about_ulcos/home/php, 2010.
17. C. Doblin and G.A. Wellwood, "TiRo™ – the development of a new process to produce titanium", In *CHEMECA: Academia and Industry Strengthening the Profession*, New York, NY: Curran Associates, Red Hook, 2007), 280.
18. D.J. Sosinsky, P. Campbell, R. Mahapatra, W. Blejde and F. Fisher, "The Castrip® process – recent developments at Nucor Steel's commercial strip casting plant", *Metallurgist*, 52 (11-12), (2008), 691.
19. J.P. Birat and J. Borlee: "ULCOS, the European steel industry's effort to find breakthrough technologies to cut its CO_2 emissions significantly". In *Carbon Dioxide Reduction Metallurgy* (eds N.R. Neelameggham and R.G. Reddy) (Warrendale, PA: Minerals, Metals and Materials Society, 2008), 59.

20. D. Xie and S. Jahanshahi, "Waste heat recovery from molten slags" (Paper presented at the *4th International Congress on the Science and Technology of Steelmaking (ICS 2008)*, Gifu, Japan, October 2008, 674, Iron and Steel Institute of Japan, 2008.
21. D. Xie, S. Jahanshahi and T. Norgate, "Dry granulation to provide a sustainable option for slag treatment". In *Sustainable Mining* (Carlton, VIC, Australia: Australasian Institute of Mining and Metallurgy, 2010), 22.
22. P. Haueter, T. Seitz and A. Steinfeld, "A new high-flux solar furnace for high-temperature thermochemical research", Journal of Solar Energy Engineering – Transactions of the ASME, 121 (1) (1999), 77.
23. J.P. Murray, "Aluminum production using high-temperature solar process heat", *Solar Energy*, 66 (2) (1999), 133.
24. J.P. Murray, "Solar production of aluminum by direct reduction: preliminary results of two processes", *Journal of Solar Energy Engineering*, 123 (2001), 125.
25. M. Halmann, A. Frei and A. Steinfeld, "Carbothermal reduction of alumina: thermochemical equilibrium calculations and experimental investigation", *Energy*, 32 (12) (2007), 2420.
26. N.R. Neelameggham, "Solar pyrometallurgy – an historical review". *JOM*, February, 2008, 48.
27. R.A. Frosch, "Industrial ecology: adapting technology for a sustainable world *Environment*, 37 (10) (1995), 16.
28. B. Kurip, "Methodology for capturing environmental, social and economic implications of industrial symbiosis in heavy industrial areas" (PhD thesis, Curtin University of Technology, Perth, WA, December 2007); www.kic.org.au/files/biji
29. J.R. Ehrenfeld and N. Gertler, "Industrial ecology in practice: the evolution of interdependence at Kalundborg", *Journal of Industrial Ecology*, 1 (1) (1997), 67.
30. D. van Beers, "Capturing regional synergies in the Kwinana industrial area: 2007 status report" (Report, Centre for Sustainable Resource Processing, Perth, WA, 2007); www.kic.org.au/files/70724_csrp_capturing_regional_synergies_in_the_kia_2007_report_final
31. R.N. Stavins, "Experience with market-based environmental policy instruments" (Discussion Paper 01-58, Resources for the Future, Washington, DC, November 2001).
32. S. Whitten, M. van Bueren and D. Collins, "An overview of market-based instruments and environmental policy in Australia", In *Market-based Tools for Environmental Management: Proceedings of the 6th Annual AARES National Symposium (eds S. Whitten, M. Carter and G. Stoneham)*, 2004; www.ecosystemservicesproject.org/html/publications/docs/MBIs_overview.pdf
33. W.J. Rankin, *Minerals, Metals and Sustainability: Meeting Future Material Needs* (Collingwood, VIC, Australia: CSIRO Publishing, 2011), 367-381.
34. *Vision 2050: The new agenda for business (*Conches-Geneva, Switzerland: World Business Council for Sustainable Development, February 2010); <http://www.wbcsd.org/web/projects/ BZrole/Vision2050-FullReport_Final.pdf>.