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Towards cleaner production: barriers and strategies in the base metals producing industry

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Abstract

The most pressing environmental problems of post-mining base metals production are solid waste production, gaseous emissions, and a high energy use. Most of the present solutions to clean up the post-mining base metals production can be characterised as incremental, end-of-pipe technologies. More sophisticated, radical solutions are scarcely implemented.

The purpose of this study is to identify the barriers that impede the implementation of more radical solutions, with the aim to design strategies towards cleaner production in the base metals producing industry. The paper conceptualises the radicalness of a technological innovation, and presents the current base metals production processes, their environmental impact, and cleaner technologies. The most important barriers for radical innovations appear to be the cost of investment, the high risk involved in committing capital to unproven technology, and the intertwinement of the current production system. The paper presents firm-internal, inter-firm and firm-external strategies to overcome these barriers.

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1. Introduction

As a result of the rapid increase in human activities since the industrial revolution, huge quantities of resources and energy have been consumed in remarkably short time. This mass consumption, and the associated industrial production, has far-reaching influences on the earth's ecology, exhausting non-renewable resources (e.g. oil, gases, ores) and causing severe environmental problems by polluting the air, water and soil.

However, many possibilities to reduce the environmental burden of industrial production exist. For example; optimisation of the environmental performance through good housekeeping and total quality management, appropriate end-of-pipe techniques, recycling of waste and non-renewable products, substitution of, or a ban on the use of environmentally unfriendly produced products, or by incremental and more radical technological innovations.

Technological innovation is an important factor for economic growth and seems to play a central role in the long-term development of cleaner production [1,2]. Hence, this paper focuses on the technological innovation perspective.

Studies have shown that in the industrial North the efficiency of production with respect to the claim on the environment needs to increase by a factor 4–50 over the next 50 years, in relation to the 1990 levels [1–5]. That is because much better results will be necessary over the next 50 years to achieve absolute reductions in materials and energy consumption. Taking into account that since Third World countries will almost inevitably increase their consumption of energy and materials as

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they industrialise and raise their living standards, the need for more radical, system innovations towards cleaner industrial production is quite evident. Thus, to meet this cleaner production challenge, adaptation or improvement of existing technology by only incremental innovations will not be sufficient. Leaving existing methods of improvement and looking for a fundamental renewal of technology, and complete new, radical technological innovations will be essential in order to achieve the required improvements in environmental efficiency in the future. Yet, implementation of such radical, breakthrough technologies is not easy to initiate. It is necessary to understand the driving forces for cleaner production at a micro-level within the firm. Accordingly, this paper focuses primarily on the perspective of the firm, taking the base metals producing industry (i.e. the production of zinc, aluminium, and iron/steel) as an example.

Studies of technological development in scale-intensive firms, such as the base metals producing industry, have shown that radical change towards cleaner industrial production is problematic [6,7]. More radical solutions for some environmental problems are available, but in practice they are scarcely implemented, because the established production technologies in the base metals industry are made up of mature technologies, which are rather difficult to change. For example, the conventional Hall-Héroult aluminium reduction process is more than 100 years old. These mature industrial technologies are part of highly embedded production systems, both technologically and socially. This makes it very difficult to redirect these processes quickly and effectively towards cleaner production, even when the need to do so is generally acknowledged. It is necessary, therefore, to analyse the nature of this entrenchment.

Accordingly, the purpose of this study was *to identify barriers which impede implementation of more radical innovations, in order to develop strategies that could contribute to the base metals industries' transition towards cleaner production.*

Why is the base metal, producing industry an interesting case for the study of the driving forces towards more radical cleaner production?

Producing large volumes of commodity products, the base metals producing industry is a relatively polluting industry, causing severe environmental problems, such as:

- production of large amounts of solid waste (e.g. jarosite, gypsum, spent pot linings, slag),
- emissions of airborne and waterborne pollutants (e.g. SO_2, NO_x, fluorides, dioxins),
- high energy use, and CO_2 emissions,
- depletion of non-renewable natural resources,
- moderate recycling rates and difficulties with secondary production (e.g. for complex aluminium alloys).

These environmental problems emphasise the need to study cleaner production alternatives in the base metals producing industry, both incremental innovations to tackle the relatively small problems on the short-term, and radical innovations, to obtain higher environmental efficiencies on the long-term.

We can discern various steps in the whole base metals chain, going from cradle to grave. Fig. 1 shows the base metals production and consumption chain.

This study focuses on post-mining base metal production, with the metal ore as input material and the primary, non-manufactured base metal as output. This primary metal can be processed further by additional processing stages to value-added applications, such as alloys and composite materials, or comes back in the metals production system via recycling and secondary production.

The structure of the paper is as follows: the first section conceptualises the radicalness of a technological innovation concerning metals production. The subsequent section provides a brief description of the conventional production processes for zinc, aluminium and iron/steel and their environmental impact. Various technological alternatives for base metals production are

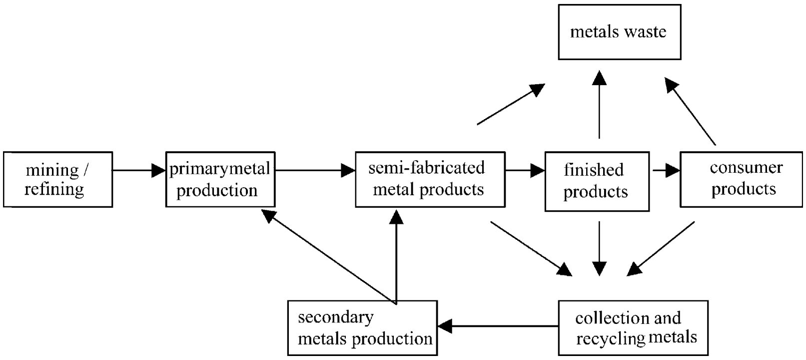

Fig. 1. Base metals production and consumption chain in general.

presented along a gradual scale of radicalness of the innovation. Based on six case studies in the metals industry, the barriers for more radical technological innovations are categorised and illustrated with some examples. The analysis of barriers provides starting points for radical technological change at various levels. Strategies are presented at the firm-internal, inter-firm and firm-external level, and the paper ends with some concluding remarks.

2. From incremental towards radical innovations: conceptualisation

A significant distinction exists between a technological innovation involving minor technological changes, which control, adjust, renovate, modify or improve a current technology based on an existing principle (and often with a low degree of new knowledge), and a technological innovation that involves major changes of technological directions with entirely new technologies, products, processes and/or systems, and a high degree of new knowledge. This distinction is often discussed in terms of incremental versus radical innovations. Yet, technological innovations are not just incremental or just radical. For our purposes, the degree of radicalness of a technological process innovation is interesting, and a technological criterion is used to determine the extent to which an innovation constitutes a radical departure from the existing production process. Technological innovations can be further divided on a gradual scale, which enables us to be more precise in describing the specific process steps to produce the primary metal, and in describing the technological innovations that can take place in those steps. In fact, it is not just incremental innovation on the one hand and radical innovation on the other, but degrees of radicalness exist in between, with technological change representing points in a continuum. Furthermore, we define the conversion of the ore from one configuration into another as *one step* in the primary base metals production. For example roasting, leaching, purification and electrolysis in primary zinc production are regarded as four steps [8].

Accordingly, we define an increasing ‘radicalness’ scale of technological innovations for base metals production as follows:

- *Auxiliary technology*: auxiliary technologies include all the supporting technologies to monitor and control the existing production process, and all the logistics and technological infrastructure that are incorporated. In fact, the software (e.g. process parameters) is adjusted without changing the hardware, such as adjustment of process control by automation.
- *End-of-pipe technology*: end-of-pipe technologies can be defined as all the technology (hardware) added at the end of the usual processes to decrease the release of environmentally problematic emissions. No changes take place within the hardware of the existing process. An example is the installation of a sulphur dioxide gas cleaning system to treat the gaseous emissions from metal production.
- *In-process technology*: in-process technologies include improvement and application of the existing technology, and the changes are integrated within the process hardware of the existing production steps. These technological innovations can be subdivided into:
    - *One-step change in the production process, retaining the same process principle* (no process conversion): this implies adjustments in single machines, in single steps of the entire production process. The adjustments do not affect the previous step(s) or following step(s). An example is the reversal of a vessel in one production step, which gives rise to an increased level of efficiency.
    - *One-step change in the production process, applying a different process principle*: this generally implies a departure from current practices, regarding a specific process step. Since no other steps are involved, the input and output characteristics are very similar to those from the existing practices. An example is the change from a sulphate to a chloride milieu in the leaching step of zinc production [8].
    - *Two to three step changes in the production process*: replacing one step often affects other steps in the process. In this category, we focus especially on those changes, which also involve adjustments in the following and/or previous steps. Pressure leaching in zinc production, for example, combines the first two steps of the conventional zinc production process into one new process step [8].
    - *More than three step changes*: generally, this implies redesigning a major part of the production process. Leaching, purification, and electrolysis e.g. were new production steps in going from a pyrometallurgical to a hydrometallurgical route in zinc production [8].
- *Breakthrough technology*: breakthrough innovations include an entirely new production process principle, or a completely new technical plant design. Departure from the conventional hardware is a necessary prerequisite. Bio-leaching, for example, is a potentially cleaner production process for some metals, since it can obviate the need for the energy intensive and traditionally polluting roasting, smelting, and refining stages [9]. Changing from

Table 1
Degree of radicalness of technological innovations in zinc production [8]

Technological alternatives	Radicalness of technological innovation						
	Auxiliary technology	End-of-pipe technology	In-process technology				Breakthrough technology
			1-step: same principle	1-step: different principle	2–3 steps	> 3 steps	
Optimisation electrolysis cell	+						
Gas cleaning		+					
Jarosite → goethiteleaching			+				
Sulphate → chloridemilieu				+			
Direct leaching					+		
Pyrometallurgy → Hydrometallurgy						+	
Direct zinc making							+

> pyrometallurgical to hydrometallurgical production of zinc is another example of a breakthrough technological change.

Table 1 presents schematically the radicalness of technological innovations in the zinc production process [8].

Most companies, when introducing changes in their production process, stay within the first three stages of technological change that is applying auxiliary technology, end-of-pipe technology or a one-step change of the production process thereby retaining the same production principle. Thus, the bulk of process changes have an evolutionary, incremental rather than a revolutionary radical character. It is interesting, therefore, to study the barriers, which constrain the development and implementation of more radical technological change in these companies.

This study was performed through six comparative case studies of the production of zinc, aluminium, and iron/steel, respectively, in which both incremental and more radical innovations were studied (see Table 2).

These case studies were based on semi-structured interviews with internal company representatives of the zinc, aluminium and iron/steel producing industry, working either in R&D laboratories, engineering, production plants, or as strategic or environmental managers. Various external representatives were also interviewed, such as researchers in universities, and in (inter) national governmental and environmental organisations. The case studies were further based on qualitative document analyses, such as scientific articles, annual reports, patents, and newspapers [10].

3. Current base metals production, environmental impacts, and cleaner technologies

This section presents a brief description of the current zinc, aluminium and iron/steel processing technologies and their environmental impact. The section ends with a schematic overview of some technological alternatives for cleaner production, in increasing degree of radicalness of the innovation.

3.1. Production of zinc

The common process to produce zinc is the hydrometallurgical roast-leach-electrowinning process, consisting of four basic steps: roasting, leaching,

Table 2
Case studies related to incremental and more radical innovations

Metal	Environmental problems	Technological innovation	
		Incremental	Radical
Zinc	jarosite, gypsum waste SO_2 emissions energy use (+CO_2)	Standard zinc production process (*Outokumpu Zinc, Finland*)	Use of low-iron zinc sulphide ore in zinc production process Jarosite treatment process (*Budel Zinc, The Netherlands*)
Aluminium	energy use (+CO_2) red mud, spent pot linings waste SO_2/, PAHs, fluorides emissions	Standard Hall-Héroult process (*Aluminium Delfzijl, The Netherlands*)	Following inert anode developments Point feeding alumina (*Hydro Aluminium, Norway*)
Steel	NO_x, SO_2, VOC emissions dioxins, slag, dust	Optimisation blast furnace technology (*British Steel, UK*)	Cyclone converter furnace technology (*Hoogovens Steel, The Netherlands*[a])

[a] In October 1999, British Steel merged with Koninklijke Hoogovens into a new company called ‘Corus’ since then. As the research for this paper took mainly place before the merger, between 1970–1997, the old names Hoogovens and British Steel are used in this study.

purification and electrolysis. Zinc concentrate undergoes fluid-bed roasting to convert zinc sulphide into zinc oxide. After roasting, zinc oxide, sulphur dioxide and ferrite are formed. SO_2 gas is treated for mercury removal and is directed to the H_2SO_4 plant, where concentrated H_2SO_4 is obtained as a by-product. Zinc oxide is then leached in a dilute sulphuric acid solution to dissolve zinc and other metals like cadmium and copper, while eliminating iron and a large part of the impurities as a jarosite or goethite residue. The solution of zinc sulphate thus obtained is purified to recover the valuable metals such as cadmium and copper, and to eliminate elements, disturbing electrolysis. During electrolysis, zinc is deposited on aluminium cathodes, which are stripped mechanically. H_2SO_4 is regenerated and recycled to leach the roasted concentrates. The stripped sheets are melted in induction ovens and are alloyed or cast into zinc slabs or blocks [11]. Fig. 2 presents the hydrometallurgical zinc production process.

The most important environmental problems of the zinc production process are the high electricity consumption (approx. 15 GJ_e/ton of zinc, of which electrolysis uses approx. 80%); the production of large amounts of the iron-bearing residues jarosite or goethite, and gypsum (approx. 0.6 ton jarosite and approx. 0.06 ton gypsum are formed/ton of zinc produced); and the emission of SO_2 (approx. 0.004 ton/ton of zinc produced) [11]. Recycling of zinc is rather difficult because of the dissipated use of zinc as a sacrificial protective coating in cars, as roof gutters and in crash barriers.

3.2. Production of aluminium

Bauxite is the main raw material for the production of aluminium. Aluminium is extracted from bauxite in the form of alumina (Al_2O_3) in the Bayer process. An aluminium production operation normally consists of an anode baking plant, an electrolytic reduction plant and a casthouse. In the Hall-Héroult process, alumina is reduced to molten aluminium metal by means of electrolysis in a series of electrolytic baths. The reaction involves the use of electricity and carbon anodes. The electrolytic bath consists mainly of molten cryolite, which is a fluoride compound and the only medium into which alumina reasonably dissolves. A carbon cell lining is used as the cathode. Liquid aluminium (>99% purity) is formed at the cathode, and is cast into ingots. There are two major types of reduction processes, the Søderberg and the prebaked process, the main difference between them being the design of the anodes [12,13]. Fig. 3 shows the Hall-Héroult electrolysis process of aluminium.

The entire primary production process of aluminium, including bauxite extraction, alumina production, transport, the Hall-Héroult process (electrolysis and anode production), and fluoride production, requires a very large amount of electric energy (approx. 72 GJ_e/ton of aluminium), of which the Hall-Héroult process uses about 80%. About 60% of the electricity used to produce aluminium comes from hydroelectric power. In that case, the total amount of electric energy is about 48 GJ_e/ton of aluminium [13].

Aluminium is being recycled in quite substantial amounts (>60%) [14], depending on its application mode. It is relatively easy to recycle aluminium that is used in construction and transport, but recycling is more difficult for aluminium used in packaging. Energy savings are the most important incentive for recycling, because secondary aluminium production requires only about 5% of the energy needed for the primary production of aluminium.

Besides the very high energy consumption of aluminium production the extraction of aluminium from bauxite into alumina in the Bayer process produces red

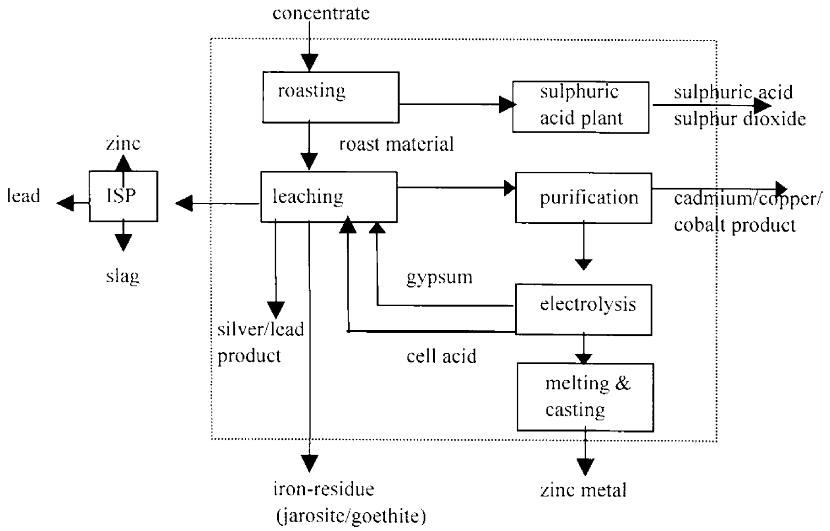

Fig. 2. Hydrometallurgical zinc production process.

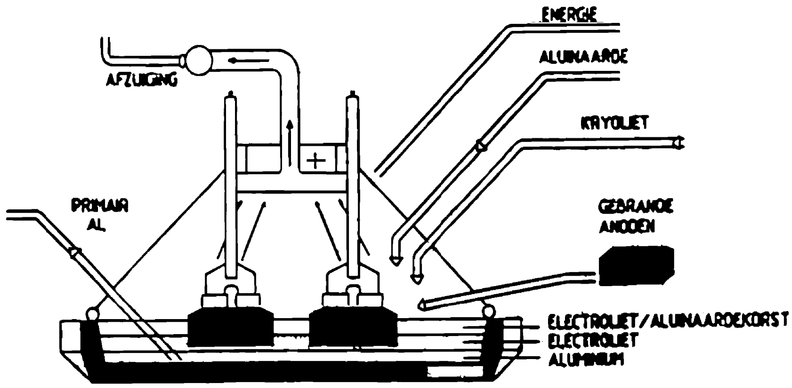

Fig. 3. Electrolysis of aluminium.

mud waste. The waste gases from the reduction cells and anodes in the Hall-Héroult process contain fluorides, dust, SO_2, CO_2, CO and minor quantities of pitch volatiles. About 20% of the latter consists of PAHs (polycyclic aromatic hydrocarbons) [12]. Fluoride compounds are an integral part of the electrolytic bath, from which gases and dust, containing fluorides, are released. CO_2 is formed when anodes are consumed during electrolysis. The greenhouse gases CF_4 and C_2F_6 are primarily formed during anode effects in electrolysis. Furthermore, wastewater and solid waste, e.g. dust, cathodic waste (spent pot linings), anodic waste and aluminium dross is produced containing fluorides, heavy metals, and PAHs [13].

3.3. Production of iron/steel

The most conventional routes to produce steel are integrated steel production, scrap melting in electric arc furnaces, and blending scrap with sponge iron or other forms of scrap substitutes as a feed to the electric arc furnace (EAF). In this paper, we focus on the widely used integrated steel production process. This process consists of coke making, ore agglomeration, iron making and steel making. The process relies mainly on virgin ore as the iron source. During ore agglomeration (sintering/pelletising), the fine iron ore is converted into particles suitable in size for charging into a blast furnace. The coke is produced in coke ovens where the volatile and non-volatile components of the coal are separated. Then, pig iron is produced in the blast furnace, using coke in combination with injected coal or oil to reduce (sintered/pelletised) iron ore to pig iron. The molten pig iron, which has some carbon and silicon, is then intermittently tapped from the hearth and the hot metal is delivered to the steel making unit where it is transformed into steel in the basic oxygen furnace, through the injection of oxygen, oxidising the carbon in the hot iron metal; the steel is then treated in ladle furnaces before being continuously cast into slabs, billets and blooms. Further deformation and shaping processes take place to obtain the almost finished product, which may include hot or cold rolled thin sheet (e.g. plates, bars, rod, tubes, profiles, wires, rails). Finishing is the final production step, and may include a number of different processes, e.g. galvanising, annealing, pickling and surface treatment [15,16]. Fig. 4 presents the iron and steel production process.

The most important pollutants of iron and steel production are particulates, NO_x, SO_2, and dioxin emissions by the sinter plants, volatile organic compound (VOC) emissions by the coke ovens, blast furnace slag, rolling mill waste, pickle liquor waste, iron- and steel making slags and waste oils and greases.

When it comes to recycling, steel appears to score very strongly, being the most recycled material, with an overall recycling rate of between 50% and 67% [16]. The emission of CO_2 is directly coupled to the energy

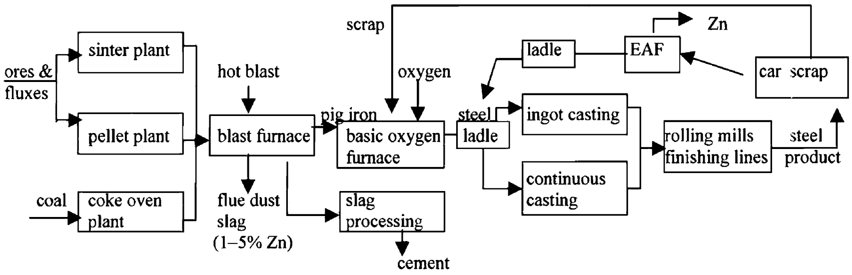

Fig. 4. The iron and steel production process.

Table 3
Alternatives for cleaner production of zinc, aluminium, and iron/steel [10,12,14]

Radicalness innovation	Cleaner production alternatives		
	Zinc	Aluminium	Iron/steel
Incremental	Desulphuring SO_2 emissions	Desulphuring emissions	Coke oven gas cleaning
↓	Re-use gypsum, jarosite, goethite	Point feeding alumina	Improving energy efficiency
	Improving energy efficiency	Improving efficiency of electrolytic ovens	Change pellet/sinter %
	Melting recycled Zn	Improving energy efficiency	Powder coal injection
	Direct leaching (high press/atmospheric)	Use carbon anodes with desulphurised coke	Re-use zinc coated steel, slag
	Hematite process	Melting recycled Al	Jumbo reactor, formed non-recovery coke oven
	Jarosite treatment	Inert anode technology	Full, balanced oxygen blast furnace
	Use low-iron zinc sulphide ore	Closed system process	Direct reduction processes
	New/inert anode technology	Carbothermic process	Smelt processes
Radical		Alcoa process	Iron carbide processes

consumption of the whole production process. The total energy use of the integrated steel production process is approximately 5.6 GJ_e/ton of steel, of which the blast furnace process uses more than half (approx. 4.3 GJ_e/ton of steel) [15,17].

The most important options for cleaner production of zinc, aluminium, and steel, are schematically summarised in Table 3, in increasing degree of radicalness [11,13,15].

Table 3 shows that many alternatives for cleaner base metals production do exist. These alternatives are in various stages of technological development that is laboratory scale, design stage, pre-commercial, and commercial stage. Yet, the more radical alternatives are not easily implemented within base metals producing firms.

4. Barriers to cleaner production in the base metals producing industry

Why are the more radical cleaner technologies not easily implemented? The case studies revealed many barriers for the implementation of more radical cleaner technologies, which could be classified as follows:

- Economic barriers
- Systemic characteristics
- Knowledge infrastructure
- Legislative context
- Organisation and culture of the firm
- Stage of technology development

Below, a brief description of the various types of barriers is given, illustrated with examples from the case studies.

4.1. Economic barriers

Financial constraints play a prominent role in the rigidity of the conventional base metals production processes. Enormous capital investments are required for radical technological changes, which involve many production steps in base metals production. Well-established processes have large-scale advantages, and often are still very profitable, giving adequate returns on investments, after the machinery has already been depreciated. A striking example is the observed investment-lag in aluminium production, due to the high capital intensity in the reduction step of aluminium. It has kept old potlines alive for up to 40 years or even longer. Improvement of operational cost of the most advanced technology does not match the capital element of replacing old capacity with modern potlines. A respondent of Hydro Aluminium declared: "*all the big aluminium smelters have come up to the same plateau regarding innovativeness and nobody has been able to make a real breakthrough in aluminium reduction technology*".

The market price of base metals is cyclic and for zinc and aluminium it is determined at the London Metal Exchange (LME). It is very difficult to calculate the environmental costs in the price of the metal. In fact, base metals' commodities provide little scope for product differentiation between the individual producers and, assuming a standardised product quality, competition is based predominantly on costs. The commodity market for base metals, therefore, provides a considerable incentive to produce at the lowest cost. The competition among metals producers is very strong, for example between steel and aluminium, and even with other material producers, for example the plastics and glass industry. This competition is based primarily on price, determined by the costs of energy and materials input, and the profit from the well established, mature production processes.

Furthermore, firms' quarterly profit-figures are becoming increasingly important, which could also impede long-term decisions. All capital investments for the metals industry including radical innovations are huge and thus long-term.

All these factors increase the perceived risk for base metals producing companies considering investing in radical new technologies. Up scaling of a new unproven technological development is a risky activity, which will give rise to losses if the new technology does not work.

4.2. Systemic characteristics

An enormous physical intertwinement exists between base metals production units and the extraction of minerals, the generation of electricity, the production of co- and by-products (e.g. combined zinc/lead/cadmium production), the use of recycled metal, and the treatment of liquid and solid waste and gaseous emissions. This gives rise to a complex industrial production system. The presence of mines, hydroelectric power, and an accessible physical infrastructure (e.g. rivers, harbours, roads, railways) determines to a large degree the presence of base metals production in a certain location. A representative of the steel industry expressed the consequences of the intertwinement as follows: "*the most important barrier for implementation of new technologies is the difficulty getting alternative new technologies within the existing infrastructure*".

Base metals companies often have long-term contracts with their raw material suppliers and customers, or they form technological alliances with other companies, which leaves not much room for experiencing with radical technologies, and which keep them in their conventional production paradigm. After all, the risks of failure associated with implementation of radical, unproven technologies in large-scale base metals producing firms can be considerable.

4.3. Knowledge infrastructure

Base metals companies often have small R&D departments, only used for troubleshooting and process optimisation, without extended firm-internal or inter-firm knowledge networks for the development and exchange of scientific and technical know-how about new (cleaner) production methods. In addition to internal know-how exchange, (informal) contacts and co-operation with universities and technical institutes, and joint research projects with other firms are important. As Outokumpu Zinc and Hoogovens Steel have clearly shown, the technology developers and suppliers are often the integrated metals producers themselves. The availability of an extended firm-internal technology network including technical specialists is essential. The reason is that a commercially proven technology needs to have been demonstrated in commercial production for a sufficiently long period of time. This means that there has to be a first user for this new technology and typically that is usually the company that has developed it. The company has invested in the development and is thus, committed to the technology and knows the technology and related risks better than an outside company, especially in the case of major changes in the production process principles and core equipment. Thus, strategic technology development which aims at radical improvements is typically carried out by fairly large producers with a strong and active R&D. Sharing process technology occurs more in the open, ECSC (European Coal and Steel Community) supported steel industry than in the relatively closed and conservative aluminium industry, which has always been exposed to high competition.

4.4. Legislative context

Some companies are rather successful in circumventing drastic government regulation. In fact, they often lobby for more time to carry out research on environmentally sound alternatives.

In some instances, however, external pressure from authorities or environmental movements can motivate companies to think about alternatives for cleaner production.

Budel Zinc has clearly shown such circumventing behaviour. The company was forced by the authorities to find a definitive solution for its jarosite waste, which had been stockpiled for years. The company tried to delay the development of a jarosite treatment process, by asking for more development time and a temporary licence for a new jarosite storage pond. When the external pressure from the authorities became stronger by not giving a license for a new jarosite pond anymore, the company was forced to find a solution for jarosite or otherwise it would have had to have shut down its zinc production plant.

The absence of international environmental legislation and a lack of harmony between national legislation, often impedes radical innovation, because only a few, mostly large, companies have been able to bear the risks and high costs of development of cleaner production alternatives by themselves. As the Budel Zinc case study has shown, the jarosite treatment process ultimately failed, because other companies did not support co-development of the new process.

4.5. Organisation and culture of the firm

The absence of top-level advocacy towards cleaner production, the absence of environmental management capacities, and the absence of a clear long-term technology (R&D) strategy could be important barriers for more radical innovations. A technology manager of Budel Zinc stated: "*With new processes it is always the question who dares to make the choice for a new process,* *which is not yet 100% proven technology. Someone must dare to say: 'we are going to do it'*". The size and character of the company (i.e. openness/innovator/imitator) are also important influences on its innovativeness [6].

Common practice and traditional production technologies are mostly very dominant in the base metals producing industry. For example, the conventional Hall-Héroult aluminium reduction process is already more than 100 years old. The historical context of the base metals producing company has created fixed traditions and a conservative culture with certain standard routines. Employees are often reluctant to work with procedures and substances other than the ones they are used to.

Metals companies are very sensitive with regard to their image: nowadays, there is a trend in large industries to have a green reputation and to be open and willing to co-operate in environmental issues that are important for the society as a whole. Besides the corporate green image, the personnel at lower levels in the organisation need to become conscious of environmental aspects.

Companies also differ in their perceptions of what they consider the short- and long-term. Usually, companies are only looking 5–10 years ahead, and they are not thinking of possible environmental effects and preventive measurements in the long-term (25–50 years).

4.6. Stage of technology development

The development stage of the technology itself could be a limiting factor for the innovativeness of a company. The development stages include: the R&D stage, design and development stage, pilot plant stage, pre-commercial stage, and finally the commercial stage. The development of inert anodes in aluminium production, for example, is impeded because scientific knowledge is not developed yet, necessary to solve all the technical problems related to the use and up scaling of these anodes in the aluminium production process.

A representative of the European Aluminium Association said: "*I cannot see a major technological breakthrough in terms of a completely new process, because there is nothing out on the horizon. There is a technological research barrier*".

In conclusion, multiple barriers are impeding the implementation of more radical cleaner technologies in the metals producing industry. These barriers may also influence each other. For example, organizational intertwinements such a long-term cheap energy supply agreements in the established aluminium industry could complicate the development of energy-saving technologies in aluminium production.

The study revealed that implementation of radical cleaner technologies is a complex problem, which makes it difficult to design single strategies to overcome these barriers. Or, in the words of a senior vice president of research and development of Outokumpu: "*New technologies seldom emerge. Incremental improvements are made continuously with good success, new ideas are presented frequently, but commercially significant quantum leaps are rare.*"

In the next section, we suggest some tentative starting points for strategies towards cleaner production on the firm-internal, inter-firm, and firm-external level.

5. Strategies towards implementing cleaner production in the base metals producing industry

Various strategies can be proposed to overcome the identified barriers to the implementation of more radical cleaner technologies. This paper gives an overview of the strategies towards cleaner production, at the *firm-internal*, the *inter-firm*, and the *firm-external level.*

5.1. Firm-internal and inter-firm strategies

1. Re-enforcement of existing firm-internal networks between R&D, engineering, production, strategy, the environmental department and top management. Dedication of top management, the development of a long-term technology strategy (25–50 years), and the incorporation of environmental management in business activities is especially important for the implementation of more radical cleaner technologies. For radical innovations, departure from the established production process is a necessary prerequisite, and the whole firm-internal network needs to be convinced of that necessity. Therefore, specific firm-internal relations should be strengthened: the R&D should be more involved in the laying down of long-term technology strategies; a powerful innovation champion, who can direct and push the radical innovation at various layers within the company, should be found internally. Stimulation of strategic and corporate research funding, instead of business unit driven research, is another driving mechanism within the firm.
2. Formation of inter-firm knowledge networks. Regarding the steel industry, a lot of research is performed in European Coal and Steel Community (ECSC) projects, where at least three or more steel producing firms work together in joint research projects. These joint research projects are especially fruitful in the pre-competitive stage. Relations between firms should be structured to include shared education and training, risk sharing agreements and joint agreement on performance measurements. An example is the joint development of the cyclone

converter process by Hoogovens, British Steel and the Italian company Ilva.

3. Strengthening of the existing or formation of new connections with public R&D facilities (universities, technological institutes) by means of co-operation with PhD students, professorships, contract research, conferences, university courses, publications, etc.
4. Cross-fertilisation of knowledge within and between firms. Exchange of knowledge and new ideas of one metals' production method to another within large integrated firms could be very fruitful. For example, at Outokumpu the flash-smelting technology in copper production had lead to the use of the same kind of technology for nickel production. At the moment, Outokumpu is even thinking of using the flash-smelting technology as a new technology for more environmentally friendly zinc production. In addition, cross-fertilisation can also take place *between* firms, for example when two companies form strategic alliances, thereby taking mutual advantage of each other's technological knowledge and resources. This was for example the case between Hoogovens and British Steel in the first developments of the cyclone converter process.
5. Relating the firms' image to their cleaner production performance, which could give the firm a competitive advantage in the long-term. Although the 'environmental imperative' is most often regarded as an external pressure to which firms must react, there is emerging evidence, particularly in the manufacturing sector, that some firms regard the environment as a new strategic arena. Firms are taking a proactive stance towards the environment to capture a competitive advantage. There is little evidence that the base metals producers are seeking competitive advantage through the marketing of 'green' metal products, with the possible exception of the aluminium industry, promoting aluminium-based lightweight cars [9]. But the 'green image' consciousness is growing in the steel industry which does not want to be regarded anymore only as a commodity producing industry, but as an industry that adds value to metals and wants to sell environmentally sound products. Process development is regarded as an important instrument for developing better and environmentally compatible products at lower costs.
6. Rival companies should work together and share risk on the development of risky, costly, unproven technological developments on a more regular basis. One of the studied aluminium companies finds joint research projects advantageous. When the costs are put together, the companies have a bigger scope. With smaller amounts of money each company can participate in a huge program with the advantage that many other international companies are joining. The research work will thus be carried out in either horizontal or vertical joint ventures among a few major companies to share the risk and utilise each other's core competencies. May be this could be stimulated by the European Union giving some companies exemption of the anti-cartel formation law for a certain period.
7. Shared responsibility through the production chain. Customers could put pressure on metals producers by threatening that they only want to buy green produced metal in the future. Metals producers could do the same upstream the production chain by pressing raw material-, energy- and machinery suppliers to move towards cleaner production methods. One of the studied aluminium companies actually sends people to the alumina refineries to examine if the alumina is produced environmentally friendly, and if the refiners have systems that protect the environment. The reason behind is that the aluminium company wants to be sure that if they sell their aluminium products they have an image of being environmentally friendly. Using Environmental Management and Auditing Systems (EMAS) as a quality system is now becoming a trend in the aluminium industry, at least for the larger companies.

5.2. *Firm-external strategies*

1. The sensitivity of metals producing companies to external pressure. Continuing pressure on metals companies' environmental performance by the authorities and environmental movements has proved to be a fruitful strategy to force companies to change towards cleaner production. First, this could be done by making the base metals producers responsible for cleaner production themselves, e.g. by using Voluntary Agreements. In the Netherlands, the base metals industry has Voluntary Agreements with the authorities since 1992. Second, governments could directly intervene in the current polluting production process by imposing more severe environmental legislation. This instrument is used in all the studied cases. Thirdly, the government could provide positive stimuli by investing in joint (public) research projects for the development of unproven cleaner technologies. In Norway, the National Reach Board (NTNU) stimulates long-term research development projects in the Norwegian aluminium industry. Fourth, pressure is also exerted on the metals producing companies via media, such as newspapers, and television. Especially the non-governmental environmental organisations, such as Greenpeace and Earth Alarm use this instrument to bring the polluting activities of the metals industry under the public's attention.

2. Creation of conditions for pre-competitive research. The government need to stimulate research on cleaner production in public R&D facilities (universities/institutes) creating a fundamental basis for the development of more radical alternatives in the metals industry, especially when this industry is not able to develop these technologies themselves. Small market niches should be created for the introduction of cleaner production methods.
3. Stimulation of government-industry partnerships. The government could introduce price-measurements incentives to stimulate selective cleaner technology development. The government could also act as a pro-active launching customer by buying only green metal products.
4. Creation of 'green metal is good' incentives at the demand side of the production chain. Therefore, consumers should trigger generation of product choice and green labelling of primary produced metals. The cases showed that steel production does react to 'green triggers' from their downstream customers in the production value chain.
5. Stimulation of the market introduction of green products and cleaner production methods. European branch organisations could co-ordinate this introduction, such as the European Zinc and Aluminium Institute, respectively, but also product information centres. The European Aluminium Association, for example, promotes the aluminium product as a very environmentally friendly product, because it weights less than steel and it can be recycled very often without large quality losses. International harmonisation of environmental legislation and cleaner production policies is important, first on the European Union level. This would prevent unfair competition between companies in different countries that are currently subject to varying degrees of external pressure.
6. Pressure by insurance companies on mining and base metals producing companies. A good environmental record is increasingly important in securing financial backing [9]. In the aluminium industry, for example, financial institutions are starting to pay attention to the companies' environmental performance.

6. Concluding remarks

Radical technological innovations towards cleaner production in the metals producing industry seem to be technologically possible. However, various barriers were identified which impede a fruitful implementation of these radical innovations. Starting points for strategies were developed at the firm-internal, inter-firm, and firm-external level to overcome these identified barriers.

First, the terms 'incremental' and 'radical' innovations were conceptualised by a technological criterion on a gradual scale of radicalness. Then, the current zinc, aluminium and iron/steel production processes and its environmental problems were described. Some alternatives for cleaner production were presented in increasing order of radicalness. The conducted case studies showed that various categories of barriers impede radical innovations taking place. Important barriers appeared to be: economic motives, such as the high costs of capital investments in the base metals industry and the high risk involved in committing capital to the scale up of unproven technology; the embeddedness of the physical intertwined production system and an underdeveloped available knowledge infrastructure. Thus, implementation of radical cleaner production technologies is a complex problem on various levels. In general, it can be stated that companies are concentrating more on incremental innovations because the existing infrastructure and capital investments are then already in place. Appropriate firm-internal and inter-firm knowledge network structures are very important for the implementation and diffusion of cleaner production methods.

The firm-external strategies could be translated into environmental policies for authorities and societal movements to overcome barriers towards cleaner production in scale-intensive firms, such as the metals producing industry. Competitive companies could cooperate more in the pre-competitive stage of technology development because of the high costs and risk involved in the development of radical cleaner technologies. This could be stimulated by the European Union by exemption of the anti-cartel laws.

Furthermore, the case studies showed that cleaner production depends very much on the continual knowledge build up at the supply side, such as research traditions within the firms, and also on the demand side, such as public R&D investments for the development of cleaner production methods, and customers and consumers consistently asking for green produced metals. Intensification and extension of existing industrial networks or even formation of new networks between the metals producing companies, their suppliers and customers, the governments, universities and technological institutes could facilitate developments and implementation of cleaner production processes. In particular, the horizontal, intra-sectoral networks, with universities, institutes and competitors seemed to play an important role [18]. The large integrated firms play an important role in the introduction of more radical technological innovation in base metals industry, and also the knowledge exchange between the base metals producing firms themselves. These firms often produce more than one metal, which enables exchange of ideas between the various production methods of metals. Thus, the intertwinement of the metals production system, which could be a barrier, could also be an incentive for the development of more radical innovations in other production processes in the base metals producing industry.

This paper presented preliminary results of a dissertation on transition towards cleaner industrial production. Future work will elaborate further on the barriers and strategies for cleaner production. The structure and characteristics of the various networks that are important for the development and implementation of cleaner production processes will be analysed in more detail and theoretically supported, using the concepts of technology dynamics (systems approach, network theory). These concepts will be used to obtain more insight into the relationships between the network structures, the production system and the decision-making processes and the impact on incremental and radical innovations in the base metals producing industry.

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