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Technology strategies for sustainable metals production systems: a case study of primary aluminium production in The Netherlands and Norway

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Abstract

Many firms are embracing the environmental challenge by implementing incremental changes in their production systems. Nevertheless, radical innovations are also important for achieving sustainability goals. This paper focuses on the technology strategies leading to radical innovations in aluminium production systems. It conceptualizes the radical nature of innovations, and develops a framework for analysing the technology strategies of two aluminium smelters, Aluminium Delfzijl in The Netherlands and Hydro Aluminium in Norway. From the analysis, policy instruments are proposed for a transition towards sustainable aluminium production.
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Keywords: Radicalness; Technology strategies; Sustainable aluminium production

1. Introduction

Technological innovation is one of the key strategies to address sustainable development. It is against this background that this paper focuses on large-scale, primary aluminium production operations in the developed world, which process large amounts of raw materials and are potentially major sources of environmental pollution. A high level of capital investment and long depreciation times of its production equipment characterizes this process-based industry, and most of the sector's innovations tend to be technologically incremental. As it has been argued that generally, radical technological innovations are necessary to achieve major reductions in value chain-related environmental pollution [1], this paper poses the following research question: which technology strategies stimulate radical innovations in the primary aluminium industry, and which policy instruments could reinforce these technology strategies?

The paper begins with a brief overview of the role of primary aluminium production in meeting the environmental challenge of sustainable development. Next, the radicalness of technological innovations is discussed and a conceptual framework for the analysis of technology strategies of firms is introduced. From the analyses of two empirical case studies of primary aluminium production, Aluminium Delfzijl in The Netherlands and Hydro Aluminium in Norway, conclusions are drawn regarding technology strategies for sustainable primary aluminium production. These conclusions are translated in policy recommendations aimed at facilitating a transition toward radical innovation in the aluminium production industry.

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2. Primary aluminium production and the challenge of sustainable development

The focus here is on the *environmental* challenge of sustainable development with respect to industrial production activities. Sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. As this study deals with industrial production activities, sustainable development is interpreted as environmental efficiency or eco-efficiency. The latter is defined as "the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity – through the life cycle – to a level in line with earth's estimated carrying capacity" [3].

In order to decrease environmental burden (or increase in environmental efficiency) drastic changes must be made to both consumption *and* production systems. This can include technological innovation, closing industrial production and consumption loops, altering consumption patterns, and transition management [4]. In terms of industrial production, both incremental and radical technological changes play a significant role. With incremental innovations, a 10–30% reduction of the environmental burden could be generally achieved in industry over a 50-year time-horizon but radical changes are also necessary in order to achieve higher environmental efficiencies (80–95% reduction levels) in emissions, waste and energy use.

Process and product innovation often complement one another in the metals production and metals product industry. Many of the sector's environmental problems result from its production processes and the extraction and smelting of the raw materials. This paper, therefore, focuses on *process* innovations, especially in the primary aluminium producing industry (i.e. the aluminium smelters). This mature, process-based industry is resource- and energy intensive and environmentally sensitive. The industry's major environmental impacts are as follows:

- Large amounts of red mud waste at alumina production;
- high-energy consumption during the whole primary production process;
- spent pot linings from electrolysis; and
- emissions of various airborne and waterborne pollutants
  - fluorides,
  - perfluorocarbons (PFCs),
  - polyaromatic hydrocarbons (PAHs),
  - sulphur dioxides,
  - carbon dioxides.

The industry's high-energy intensity and environmental impacts necessitate the increased application of advanced technologies, including incremental innovations to tackle comparatively minor problems and radical innovations to achieve greater environmental efficiencies. The need for primary-produced metals is escalating, due in large part to increased demand in industrialized countries and, perhaps more importantly, in developing countries, particularly China and India. This growth underscores the importance, environmentally, of promoting radical technological changes in primary aluminium production processes.

3. Radicalness of technological innovations

There is a significant distinction between an innovation requiring minor technological changes, which controls, adjusts, renovates, modifies or improves an existing technology, based on an existing principle with a small degree of new knowledge, and one that involves a major change in technological direction emphasizing the application of new systems, processes, and products, and requiring a higher degree of new knowledge. This distinction is often depicted as "incremental versus radical innovations", although innovation can lie between both extremes. For the purposes of this paper, therefore, the innovation is classified as follows (increasingly radical):

- *Incremental innovations*. These innovations include end-of-pipe innovations, auxiliary technologies, and one-step changes to the existing production process, applying the same process principle. An example is the installation of a sulphur dioxide gas cleaning system to treat gaseous emissions from metals production, or the use of point feeding in Søderberg technology in aluminium production plants.
- *In-process innovations*. These include improvements and applications of the existing technology, whereby the changes are integrated within the process hardware of existing production steps. The change from Søderberg to prebaked technology in primary aluminium production is an example of an in-process innovation.
- *Radical innovations*. These innovations imply the application of an entirely new production process principle in a company. Departure from the conventional hardware is a necessary prerequisite. It could also imply the building of a completely new production plant or decommissioning a pre-existing one. The conversion from the Hall–Héroult process to the Alcoa process, or a shift from primary smelting activities to secondary remelting or recycling activities are examples of radical innovations in the case of an aluminium company.

Most primary aluminium production companies introduce incremental changes to their production process, that is, they apply end-of-pipe technology, auxiliary technology or a one-step change to the production process. However, the capacity of these types of changes to achieve major environmental improvements is limited. Studies have shown that [5]:

- Auxiliary innovations, such as best practices, reduced spillage, and good maintenance of process installations can reduce the environmental burden by 5–50%;
- end-of-pipe technologies may reduce emissions completely, but these technologies use energy and often generate new waste streams; and
- technological change within the production processes (i.e. in-process or radical changes) can lead to major environmental gains. Emissions and waste production might be prevented and energy use optimised (e.g. co-generation of heat and power).

Thus, radical technological change is a necessary complement to these changes in achieving more sustainable industrial production. Radical change, however, will only render a major contribution to sustainable development if it is also embedded in transformations of the organizational and social structure, culture and practices related to the specific technology [6].

4. Conceptual framework for studying technology strategies

Before the various technology strategies for sustainable metals production can be assessed, the underlying mechanisms of the technology strategies must be unraveled. To accomplish this task, a *systems-network* conceptual framework is introduced. This section of the paper describes how the mechanisms influencing technology strategies could be conceptualized in the light of technology dynamics approaches, by studying technological change at two levels: at the technological systems level and at the actor network level [7].

Hughes [8] describes technological systems as including ''physical artifacts, organizations, scientific components, legislative artifacts, and natural resources. An artifact, either physical or non-physical, functioning as a component in a system interacts with other artifacts, all of which contribute directly or through other components to the common system goal. If a component is removed from a system or if its characteristics change, the other artifacts in the system will alter characteristics accordingly''. This definition of a technological system combines the internal and functional technical interrelatedness with the institutional, regulatory and economic context in which the system prevails. Thus, technologies are not merely isolated artifacts, but part of large wholes of interrelated entities which support and sustain them.

During the growth phase of the technological system, not all components grow at the same pace. Imbalances appear at the systems level, when one part of the system does not develop at the same speed with the rest of the system. These imbalances, so-called occurring 'reverse salients',[1] endanger the expansion of the technological system. Resolving reverse salients in a technological system will lead not only to the development of the system, but also precipitates new imbalances in other parts of the system. The dynamics of the sequential resolution of imbalances advance the technological system. What was once a limiting factor will subsequently be a complementary one. With regard to mature technological production systems, such as primary aluminium production, with relatively low levels of growth, a system-inherent reverse salient may remain latent, invisible or suppressed in these systems for many years. At a certain moment, due to a triggering event, these latent reverse salients could become urgent critical problems, which threaten the system's continued existence [10]. Such a triggering event could be increased system-external pressure exerted upon the system, such as environmental, governmental or market pressure, or increased system-internal pressure, such as accelerating depreciation times and business expansions programs of the firm. Whether a critical problem is translated into potential solution directions (i.e. technology strategies) depends on whether the actors in the technological system perceive advantages in pursuing available (technological) alternatives.

Technology strategies therefore require human intervention. Innovation occurs because an individual actor's decisions bring it about. Groups of actors act in concert with one another in networks, negotiating technological options. Various actors perceive the reverse salient within a technological system differently. Some regard the critical problem as severe, and one which they want to solve; others do not. The ways in which the critical problem is identified and resolved reflects the various interpretations of the actors (with specific behaviours and interests). Which actors make the technology choices, and how do these strategies take place? To answer this question, we must focus on the level of individual actors, their resources, and their organization and interactions in networks. Industrial and social network approaches deal with these aspects

[1] Hughes [9] borrowed the term 'reverse salient' from ''military historians, who delineate those sections of an advancing line or fronts that have fallen back as ''reverse salients''. In the case of a technological system, inventors, engineers and other professionals dedicate their creative and constructive powers to correcting reverse salients so that the system can functional optimally''.

(e.g. Håkansson [11], Vergragt [12], Mulder [13]). According to Vergragt [12], the creative step from a critical problem to solution directions takes place in the setting of (industrial) research and technology networks. The type of solution direction (technology strategy) depends on the conditions that enable or constrain the negotiation process between actors in the network. These conditions can be found in the network structure, in the resources, and in the interactions between the actors in the network (e.g. Håkansson [11]). Mulder [13] found that for the survival of a technological innovation during its stages of development, a number of network characteristics were of special importance. These characteristics include the extension, the heterogeneity, and the density of the network; the strength and nature of the relations between actors; and the availability of resources to the actors in the network. Thus, actors solve critical problems by interacting in research and technology networks in which they negotiate with each other about the various technology strategies. These actors are bounded by the structural constraints of the technological system, and they change their networks by entering into new exchange relationships. The amount and heterogeneity of these exchanges may change the structure and relationships of the existing research and technology networks radically. These organizational changes will result in reconfigurations at the systems level, and if the technology strategies are successful, the system can continue its existence, which in turn will encourage changes in the behaviour of individual actors and so on. Whether the chosen incremental or radical technology strategy will indeed be implemented depends, among other things, on the degree of technical and organizational intertwinement and the sunk costs of the technological system. A higher degree of physical interrelatedness of production steps makes implementation of a specific technological option more difficult. In addition, financial constraints could hinder implementation of a specific technology. Major capital investments often go hand-in-hand with the implementation of a radical change in the production system.

In sum, we put forward four main decision-making mechanisms influencing the technology strategy to be followed, as summarized in Box 1. These mechanisms will be used as the basis for the analysis of technology strategies in the primary aluminium production system.

Box 1. Mechanisms influencing technology strategies

- Reverse salient and pressure leading to critical problems at the systems level.
- Translation of critical problems into potential solution directions.
- Structure of the technology network and interactions of involved actors.
- The radicalness and implementation of the chosen technology strategies.

5. Research design

This paper draws on exploratory and qualitative research methods in order to analyse the mechanisms that influence technology strategies in the primary aluminium production industry. A case study design is applied to study the primary aluminium production system of Aluminium Delfzijl in The Netherlands and Hydro Aluminium in Norway.

We initially explored the existing primary aluminium production field by studying relevant secondary literature and visiting seven aluminium production companies (Alcan, Alcoa, Reynolds Metals in North America, Hydro Aluminium in Norway, and Billiton, Pechiney, and Hoogovens Aluminium in The Netherlands). The information gathered from these orienting company visits formed the basis from which the two comparative cases Aluminium Delfzijl and Hydro Aluminium were chosen. Next, for these two cases, some 25 semi-structured interviews were conducted with various stakeholders involved in technology strategy processes in the primary aluminium industry, working either in R&D laboratories, engineering and production plants, or as environmental and strategic managers. Firm-external representatives of the aluminium industry were also interviewed, including researchers in universities and representatives of the branch organizations (e.g. Aluminium Centrum and European Aluminium Association), provincial, national and international governmental and environmental bodies (e.g. Bellona, SFT Norway, Stichting Natuur&Milieu, and Wadden Society). The Aluminium Delfzijl case study is mainly based on written sources, including a newspaper scan of the 'Nieuwsblad van het Noorden' from 1994 until 1998.

6. Primary production of aluminium [14]

Aluminium is the most widely used nonferrous metal. It is a lightweight, high-strength, malleable, ductile and readily recyclable metal, exceeded only by iron in world consumption. The most important applications for aluminium include building and construction, such as large roof constructions, offshore installations, stairways, window frames and doors; transportation, for example in airplanes, cars, trains, ships; packaging, for example; for food and beverages; and electrical technology, such as power transmission lines, transformers and panels. Moreover, aluminium is increasingly being used in cars. The automotive industry's heightened use of the metal is driven by the need to reduce vehicle weight[2] and, with it, fuel consumption and air emissions [15].

The recycling of used aluminium products varies between the different application areas. In Europe, effective collection and recycling schemes are in place for a number of applications, and the recycling rates of aluminium in these sectors are very high, for example about 90% in the automotive industry and about 85% in the building sector. Average recycling rates for building and transport applications range from 60 to 90% in certain countries. Spent aluminium can be reused in high quality applications [16]. In the packaging industry, the percentage of recycled aluminium products is generally low, except for beverage cans (the recycle rate for aluminium cans is already above 70% in some countries, with Sweden (92%) and Switzerland (88%) as the European leaders, although the overall European average is 40%, a 10% increase since 1994 [17]). Due to its widespread use in the market place, used aluminium packaging poses a special collection and sorting difficulty [18].

Recycling 1 kg of aluminium can save about 8 kg of bauxite, 4 kg of chemical products and 14 kW h of electricity. Just over 11.6 million tons of old and new scraps were recycled in 1998 worldwide, which fulfilled close to 40% of the global demand for aluminium. Of this, 17% came from packaging, 38% from transport, 32% from building and 13% from other aluminium products [19].

In 1886, Charles Martin Hall and Paul Héroult invented the Hall–Héroult process for the primary production of aluminium from alumina. This makes aluminium a comparatively new metal, being produced in commercial quantities only for some 118 years.

Today, the aluminium industry comprises three principal sectors. The *primary* sector produces alumina, molten aluminium metal and ingot, and is dominated by the Bayer process and Hall–Héroult process. The second, the *semi-fabricated* sector, produces sheet, plate, foil, castings, wire, rod, bar and extrusions, and a wide variety of alumina-based chemical products. The third sector, *finished products*, uses products from the first two sectors to manufacture a wide variety of aluminium consumer products, such as foil and cans.

There is only one main aluminium-containing ore, which is called bauxite. The only industrial process used for concentrating bauxite into pure metallurgical alumina is the hydrometallurgical Bayer process. Because of the exceptionally high stability of alumina, the most convenient process for reducing aluminium oxide to primary aluminium metal is the electrolytic Hall–Héroult process [20].

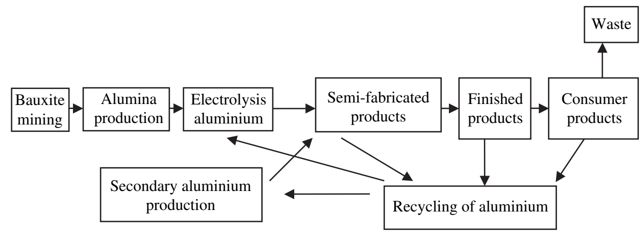

Fig. 1. Aluminium production and consumption chain.

Primary, as well as secondary, aluminium can be discerned: primary aluminium results from the Hall–Héroult process whereas secondary aluminium comes from the recycling of aluminium scrap. This study focuses on the primary aluminium production system. Fig. 1 presents a schematic overview of the aluminium production and consumption chain. Below, a brief description is given of each step in the primary aluminium production process.

6.1. Bauxite mining

With a share of 8%, aluminium is the third most abundant element in the earth's crust.[3] This makes the availability of ore supplies for aluminium production almost unlimited. Bauxite ore contains high concentrations of aluminium hydroxide minerals (40–60%), plus iron, silicon and titanium oxides as the main impurities. Bauxite is mainly extracted using open-cast mining methods and is used to produce pure aluminium oxide through the Bayer process and subsequently aluminium through the Hall–Héroult process. On average, between 4 and 5 tons of bauxite are needed to produce 2 tons of alumina, from which 1 ton of aluminium can be produced.

Major deposits of bauxite are found in a wide belt around the equator, in countries such as Australia, Guinea, Jamaica, Brazil, India, Venezuela, China and Suriname. In Europe, bauxite is mainly found in Greece and Hungary [21].

6.2. Alumina production

Bauxite is processed into pure aluminium oxide (Al_2O_3), so-called alumina, before it can be converted into primary aluminium by electrolysis. This is achieved through the use of the Bayer chemical process in

[2] This need is compounded by the increasing number of safety–mandated products, such as air bags and antilock brake systems, as well as the increasing number of consumer convenience items, such as power locks, power sunroofs, and high-watt-age multi-speaker sound systems, that add a significant amount of weight to a vehicle [15].

[3] Oxygen is the most abundant element in the earth's crust (47%), followed by silicon (28%).

alumina refineries. The basic Bayer process has remained almost unaltered since its invention. In this process, aluminium oxide is released from the other substances in bauxite in the form of a caustic soda solution, which is filtered to remove all insoluble particles. The aluminium hydroxide is then precipitated from the soda solution, washed and dried while the soda solution is recycled. After calcinations, the end-product, aluminium oxide, is a fine-grained white powder. What remains at the end of the process largely consists of oxides and hydroxides of iron and silicon. As the sludge is red, due to the iron compounds, it is called 'red mud'. Depending on the source of the bauxite, between 0.35 and 0.8 tons (dry weight) of red mud are produced per ton of alumina [22].

Alumina refineries are often located near to bauxite mines for logistics reasons. The main production areas for alumina are Australia, Central and South America, North America and Europe [23].

6.3. Electrolysis of aluminium

The most important raw materials in the production of primary aluminium are alumina, electrical energy and carbon. Primary aluminium is produced in reduction plants, or aluminium smelters, where pure aluminium is extracted from alumina by the *Hall–Héroult process*. This electrolytic process is still the most important process for the primary production of aluminium metal. The reduction of alumina (Al_2O_3) into liquid aluminium is conducted at temperatures around 950–980 °C in a fluorinated bath under a high intensity electrical current of typically 150,000 A. This process takes place in electrolytic cells, large carbon or graphite lined steel containers known as 'pots',[4] where carbon cathodes form the bottom of the pot and act as the negative electrode. Carbon anodes, the positive electrodes, are held at the top of the pot and are consumed during the process when they react with the oxygen emanating from the alumina. The reaction is based on *electrolysis* of alumina in molten cryolite (Na_3AlF_6), the only medium into which alumina reasonably dissolves. Carbon cell lining is used because of the extreme corrosive behaviour of the bath mixture. Upon the flow of current, the following overall chemical reaction takes place for the production of primary aluminium:

$$2Al_2O_3\ (\text{dissolved}) + 3C\ (\text{solid, anode}) = 4Al\ (\text{molten}) + 3CO_2\ (\text{gas})$$

More than 99% pure molten aluminium is formed at the cathode deposited at the bottom of the pot, and is siphoned off periodically. The molten aluminium is transported to the cast house where it is alloyed in holding furnaces by the addition of other metals, cleansed of oxides and gases, and cast into ingots, extrusion or rolling ingots, depending on the way in which it is processed from that point onwards in semi-fabricated and finished products.

A typical aluminium smelter consists of around 300 pots. These will produce some 125,000 tons of aluminium annually. However, some of the latest generation of smelters are in the 350–400,000 tons range. The smelting process is continuous. A smelter cannot easily be stopped and restarted. If the production system is interrupted by a power supply failure of more than 4 h, the metal in the pots will solidify, often requiring an expensive rebuilding process. From time-to-time, individual pot linings reach the end of their useful life, at which point the pots are then taken out of service and relined.

Typically, the production of 1 ton of aluminium requires 1.9 tons of alumina and consumes 0.4–0.5 tons of carbon anodes and 13,000–18,000 kW h_e/ton aluminium produced. There are, however, considerable differences between individual production plants. The consumption of electrical energy for electrolysis is about 13,000 kW h_e/ton aluminium in new plants, excluding transformation losses and the operation of other equipment. Overall energy consumption, including these elements as well as the energy required for anode production, is in the range of 14,700 kW h/ton for new plants. Design and process improvements have progressively reduced this figure from about 21,000 kW h/ton in the 1950s, a decrease of about 30% [24]. Energy consumption in Søderberg plants is higher, ranging from 15,500 to 16,500 kW h/ton aluminium produced [25].

The large impact of energy in the direct production costs of aluminium has brought about an important redistribution of production capacities and relocation of aluminium plants since the oil crisis in 1973. Plants poorly located for low cost power supply closed down, particularly those operating on oil-fired power stations. Energy may, in fact, be considered as one of the most essential raw materials for aluminium production. Cheaply negotiated power is therefore the key to the survival of the aluminium industry in Europe [26]. Worldwide, about 55% of the electricity used to produce primary aluminium comes from hydroelectric power, and the remainder, from power stations using fossil fuels (coal, oil, gas; 40%) or nuclear power stations (5%) [27].

Recycled aluminium requires only 5% of the energy required to make 'new' aluminium [28]. Blending recycled metal with new metal allows considerable energy savings, as well as the efficient use of process heat. There is no difference between primary and recycled aluminium in terms of quality or properties.

[4] An aluminium production plant may have one or more pot lines, consisting of pots electrically connected in series.

There are two types of anodes currently in use. All new pot lines built since 1975 use the modern *prebaked anode* technology, where the anodes, manufactured from a mixture of petroleum coke and coal tar pitch, are prebaked in separate anode plants. In the *Søderberg anode* technology, the carbonaceous mixture is fed directly into the top part of the pot, where 'self-baking' anodes are produced using the heat released by the electrolytic process. About one-third of global aluminium production takes place with Søderberg technology. In Western Europe, about 17% of aluminium production is carried out using Søderberg technology [29].

The annual capacities of aluminium production plants range from about 10,000 to 400,000 tons. Aluminium output increased by a factor of 13 between 1950s and the 1990s. In 2003, worldwide production of primary aluminium was 21.9 million metric tons.[5] In Europe the main producing countries are France, Norway and Germany. Table 1 presents the aluminium production per area in the world [30]. Worldwide, aluminium production plants are mainly located where suitable electrical energy sources are available, often at remote locations [31].

7. Environmental problems related to primary aluminium production [32]

The most important environmental problems related to primary aluminium production are as follows.[6]

7.1. Bauxite residues from bauxite processing

Components of bauxite include, amongst others, aluminium oxide, iron oxide, and silicon oxide. Alumina is extracted from the bauxite by the Bayer process, in which aluminium compounds are dissolved in an alkaline solution called Bayer liquor. What remains at the end of this process largely consists of oxides and hydroxides of iron and silicon. This sludge is red, and the product is therefore known as "red mud". Depending on the source of the bauxite, between 0.3 tons (for high grade bauxite) to 2.5 tons (for very low grade bauxite) of red mud are produced per ton of alumina [33]. The red mud poses storage problems due to the large amounts of solid waste. Today, it is recognised that all mining areas should be treated so that their post-mining condition is essentially indistinguishable from their pre-mining condition.

[5] The primary aluminium annual production *capacity* is 23.8 million metric tons [30].

[6] This section is, besides literature references, also based on personal communication with respondents of Billiton, Alcoa, Alcan and Reynolds Metals (aluminium companies).

Table 1
Aluminium production per area in the world [30]

Area	Aluminium production (in millions metric tons)
North America	5.5
West Europe	4.1
East/Central Europe	3.9
Asia	2.5
Latin America	2.3
Oceania	2.2
Africa	1.4
Worldwide	*21.9*

7.2. Emissions of airborne and waterborne pollutants, such as fluorides, polycyclic aromatic hydrocarbons, sulphur dioxides, carbon dioxides and perfluorocarbons

The electric aluminium reduction process and the production of anodes and electricity lead to emissions to air and water. The emissions of fluorides, polycyclic aromatic hydrocarbons (PAH), sulphur dioxide, carbon dioxide, perfluorocarbons, dioxins, and dust have particularly affected the natural environment around aluminium plants.

During the aluminium reduction process, *fluorides* are emitted from the cryolite bath (the main component being sodium aluminium fluoride) in particulate and gaseous form. The total fluoride emissions can be typically in the range of 15–40 kg/ton of aluminium, depending on the cell operating temperature, electrolyte composition, cell hooding, volume and humidity of ambient air leakage to the cell and method of crust breaking and alumina feeding. All European aluminium smelters are today fitted with gas cleaning systems. The vast majority use dry scrubbing technology, in which the used cleaning agent, alumina, and fluorides are returned to the cells for reuse, and which has a cleaning efficiency of nearly 100%. Due to scrubbing equipment, which removes 96–99% of all emissions from the pots and enables their reuse in the process, the average fluoride emissions have so been reduced to 1.1 kg/ton of aluminium (0.5 kg for new modern plants); emissions were in the range of 3.9 kg/ton in 1974 [34].

The main sources of *polycyclic aromatic hydrocarbons* (PAH) emissions in aluminium production are the production of anodes for prebaked plants and the direct electrolysis emissions from Søderberg plants. The prebaked anodes are produced from petroleum coke and pitch, and are baked in gas or oil-fired bake ovens. In modern plants, emissions from mixing operations and bake ovens are cleaned in dry scrubbing systems, where the tar components are returned to the production process. Average PAH emission rates to air from European anode plants are approximately

0.05 kg/ton of aluminium, with less than 0.01 kg/ton for the modern prebake aluminium smelters [35]. Søderberg anode paste is produced in the same way as prebaked anodes, but with higher pitch content. PAH emissions from these anodes occur directly into the potrooms from the in-site baking of the anode. Over the past 15 years, Søderberg plants have gradually changed to a dry anode technology. Through this and other process improvements, exposure to PAH inside the potroom has been reduced by more than a hundredfold, and emissions have also been significantly reduced. Current emission levels for PAH to air from Søderberg plants are approximately 0.25 kg/ton of aluminium [36].

Sulphur dioxide (SO_2) is emitted from aluminium production facilities in connection with the burning of fossil fuels in all parts of the production chain (steam production and calcinations in alumina plants, bake oven in anode plants, cast house) and, in particular, from anodes combustion in the smelters. There are two options available for reducing SO_2 emissions from the aluminium smelters. First, SO_2 emissions depend directly on the sulphur content of the petroleum coke used. When low sulphur fuel and coke is not available in sufficient quantities, wet-cleaning systems can be installed to reduce emissions according to local air quality requirements. Some substantial SO_2 emission decreases have been achieved wherever low sulphur fuel oil or natural gas is used in combustion furnaces or when wet scrubbing systems are installed. In 1994, the SO_2 emission levels were in the order of 10 kg SO_2 per ton of aluminium in primary aluminium plants [37].

It is estimated that, on a global average, the consumption of 0.5 tons of anodes (per ton aluminium produced by electrolysis) leads to an emission of 1.83 tons of *carbon dioxides* (CO_2). Including anode production and foundry, the emission is 2 tons CO_2 per ton of aluminium. The possibilities available for reducing CO_2 emissions are limited (about 1–2% per year as anode consumption decreases). Further reduction can be achieved with continued process efficiency improvement. Total CO_2 emissions for the production of aluminium by electrolysis are far less than the emission from the generation of electric power needed for electrolysis through the combustion of fossil fuels [38]. During the 1990s, the aluminium industry reduced its CO_2 by around 10% through implementing improved production techniques.

In the electrolytic process, the inorganic fluorides, the *perfluorocarbons* (PFCs), and tetrafluoromethane (CF_4), and hexafluoroethane (C_2F_6) gases are produced during the 'anode effect', which occurs when the alumina concentration in the bath is too low, resulting in a high dissipation of energy and a chemical reaction between the carbon anode and the fluoride. Anode effects are detected by a sudden increase in pot voltage drop.[7] These gases are greenhouse gases. As PFCs gases are solely caused by anode effects, reducing their frequency and duration is the primary means of reducing such emissions. This can be achieved by changing operating conditions and installing modern computer control and point feeders to improve control of alumina concentration in the bath [39]. The PFC emissions per ton of aluminium diminished by 47% between 1990 and 1997, to levels of about 0.3–1 kg/ton aluminium produced [40].

7.3. Spent pot linings from electrolysis: cathode waste

Primary aluminium production gives rise to cathode residues, so-called spent pot linings. Pot linings are used as the cathode in the electrolytic cells, and have to be replaced every 6–7 years. It is necessary to dispose of the old lining, which consists of old refractory bricks and carbon, material from the electrolytic bath, plus a small amount of cyanide, with concentrations in the range 0.1–0.3% [41]. Where landfill is used, precautions have to be taken to ensure that the waste material cannot leach out of the site through rainfall, by lining the landfill site and covering it with an impermeable liner. Groundwater and soil are continually monitored for contamination. In some plants, the cathode waste is stored above ground in dry conditions to await final disposal or recycling. The aluminium industry is currently researching other methods of cathode waste use, including extracting and recycling some of its useful components, and using the waste material as a combustion source for power generation, or as raw materials in other industrial processes (e.g., cement, steel) [42].

7.4. High-energy consumption (and related greenhouse gas emissions)

In thermodynamic terms, aluminium production requires significant energy. High-energy consumption is inherent to its primary production process. Theoretically, 31.1 GJ/ton aluminium is necessary to reduce aluminium from alumina [43], compared to the 6.8 GJ/ton iron theoretically required to reduce iron from iron oxide [44]. The *electricity* requirements for electrolysis have been reduced by more than one-third over the past 45 years. The present European average of about 13,000–15,000 kW h_e/ton of primary aluminium is still being continuously reduced through implementation of improved process technology. These changes are

[7] Anode effects result from underfeeding alumina into the cell causing reactions between the electrolyte and carbon anode at increased cell voltage. Anode effects can be prevented by computer control and point feeding of aluminium oxide.

Table 2
Technological alternatives for aluminium production

• use of Hall-Héroult principle, based on alumina and carbon anodes	
• desulphuring emissions via seawater washing	
• improved energy efficiency Bayer and Hall-Héroult process, up to 15% electricity savings	
• increase in use of hydro electric power; production only in hydro-electric power countries	
• continuously addition of alumina through point feeding	
• sealing efficiency of electrolytic ovens, better oven constructions	↓
• higher ore yields, use of other ore-compositions.	
• thermic efficiency of Bayer process	
• closing of caustic circle, less red mud formation; recycling of caustics $AlOH_3$	
• storage alternatives for red-mud (dry-mud stacking – reuse)	
• possibilities to regain byproducts such as titanium and gallium	
• improving energy efficiency	
• increase of the life span of the cathodes (by more than 8 years)	
• use of carbon anodes with desulphurized coke	
• melting recycled aluminium	
• development of inert anode technology	
• drained cell principle; bipolar H.H. cells; stable cathodes;	
• carbothermic reduction process	more radical
• Alcoa chloride process for the production of aluminium	

expected to reduce energy consumption in electrolysis by about a further 10% within the next decade. Similarly, the *thermal* energy consumption (fossil fuel consumption of primary aluminium production throughout the process chain) has been reduced by 25% over the past 20 years, and will further decrease as a consequence of further process developments and upgrading of existing installations [45]. The industrial processes of the primary aluminium industry were directly responsible for emitting 110 million tons of CO_2 equivalents in 1997, 50 million tons (45%) of which originated from the two perfluorocarbon compounds (PFCs) tetrafluoromethane (CF_4) and hexofluoromethane (C_2F_6). On average, the smelting process itself is responsible per ton of aluminium for the production of 1.7 tons of CO_2 (from the consumption of carbon anodes) and the equivalent of an additional 2 tons of CO_2 from PFC emissions[8] [46].

8. Alternatives for primary aluminium production [47]

Recent technology and equipment developments in the field of alumina are concerned with the usage of different qualities of bauxite, improvement in alumina extraction efficiency, better yields in precipitation, enhancing scale of operation, and minimizing soda losses in the Bayer process. Improvements in electrolysis involve substantial improvements in the size and design of the Hall–Héroult cells, efficiency of the current electrolysis process, metal purity, power consumption and material savings, and the development of inert anodes as a long-term goal. For reasons of sustainable production, it is important to find technological alternatives to overcome the mentioned environmental problems during primary aluminium production. Table 2 provides a brief overview of the most important technological alternatives available for primary aluminium production, from incremental to more radical technical changes [48–50].

9. Two aluminium case studies

This section of the paper analyses the most important technology strategies adopted in the primary aluminium production systems of Aluminium Delfzijl in The Netherlands and Hydro Aluminium Karmøy in Norway during the period 1959–1998 [51–56]. Box 2 provides a brief description of the companies studied.

9.1. The period 1959–1970

In 1959, a large natural gas deposit was found north of The Netherlands. In order to find a high quality destination, the Dutch Ministry of Economic Affairs suggested allocating part of the deposit to stimulate industrialization in that area. In 1961, the Billiton Company, mainly involved in mining activities and chemical developments, was studying the establishment of an aluminium production plant in Delfzijl. Billiton's plant design was based on an aluminium smelter with a production capacity of 54,000 to 60,000 tons/year, forming part of the largest production units in Europe at that time. For this purpose, two electrolysis pot lines needed to be built. Three important preconditions had to be fulfilled to achieve economically sound production of

[8] PFCs are potent global warming gases and have long atmospheric lifetimes. For example, 1 kg of PFC (CF_4) is equivalent to 6500 kg of CO_2.

Box 2. Description of the two aluminium companies

Aluminium Delfzijl (Aldel) is a primary aluminium production plant in Delfzijl in the northern part of The Netherlands. Since 1982, it has been solely a subsidiary of the Koninklijke Hoogovens Group,[9] producing steel and aluminium. In 1997, Aldel had an annual production capacity of about 96,000 tons of primary aluminium.

Hydro Aluminium Karmøy (Hydro) is a primary aluminium production plant in Karmøy, located on an island on the west coast of Norway. It is part of Norsk Hydro, having its core businesses in agriculture, oil and gas, petrochemicals and light metals. In 1997, Hydro had a production capacity of about 270,000 tons/year, and is one of the largest aluminium plants in Europe.

such large quantities of aluminium. First, the raw materials supply of alumina had to be ensured.[10] Accordingly the bauxite mining of Billiton in Surinam was important for the potential aluminium smelter in Delfzijl. Secondly, cheap energy should be available in large quantities. Around 1960, the production of 1 ton of aluminium used about 15,000 kW h of energy, leading to a yearly energy consumption of 1.5 billion kW h in the aluminium production processes at Delfzijl. Electricity generation by means of gas generators for the aluminium production was considered appropriate. Accordingly, the costs of natural gas would be decisive for profitable aluminium production and therefore, negotiations with the Dutch authorities would be necessary. Thirdly, it should be possible to market the produced aluminium at a reasonable price. The new smelter in Delfzijl was favourably situated compared to other important industrial regions within the EU, and especially in the Benelux and the north of West Germany.

The Billiton Company cooperated with the Swiss aluminium company Aluisuisse for the realization of the primary aluminium production plant in Delfzijl. Aluisuisse had at its disposal very extensive knowledge and experience in the field of aluminium production, rolling and extrusion processes. Furthermore, Aluisuisse was a suitable partner because it was aiming at aluminium markets outside the Benelux. Aluisuisse would take one-third of the shares in the Dutch smelter. In addition, Billiton asked the large Hoogovens Company to participate because of the very high investment costs of the planned smelter (about 120 million US $). Hoogovens could also play an important role in the processing of the aluminium metal, contributing with its knowledge and experience in steel rolling.

The arguments posed by Hoogovens for its participation in the aluminium project were as follows: first, they realized that the growth potential for steel in the future was limited, due to saturation of the steel market; second, they expected that steel would experience increasing competition from aluminium; third, they wished to participate in the development of a highly esteemed product as a second metal; and finally, the potential partner Aluisuisse was regarded as a highly classified enterprise. After all, the possibilities to co-operate with a renowned company within the small group of aluminium producers were limited. In addition, the contribution of Billiton, having good quality bauxite mines in Surinam, was regarded positively. It had been agreed that Hoogovens would take half of the shares, Alusuisse one-third, and Billiton one-sixth, and that Hoogovens gained the leadership of the project.

In 1965, a temporary agreement was closed with the Dutch Gasunie, which was converted into a definitive natural gas contract in 1967. This *long-term energy contract* lasted 20 years, with a renewal option of two times every 10 years. It comprised the conditions for the delivery of 13 billion cubic meter natural gas, sufficient for an annual production of 60,000 tons of aluminium for a period of 40 years (until 2006). In 1964, the NV Aluminium Delfzijl, or Aldel, was established. In 1966, Aldel produced the first aluminium at the new smelter, followed by the decision for extending the aluminium plant to a production level of 90,000 tons by expanding the two existing pot lines.

Norsk Hydro was established in 1905 to utilize Norway's large resources of hydroelectric power in the first industrial manufacture of nitrogen-based mineral fertilizer. Energy in the form of both hydroelectric power and petroleum had been the basis for Hydro's growth. In 1967, Norsk Hydro began building its first aluminium smelter, after acquiring a hydroelectric power system in the Norwegian southwestern Roldal/Suldal region in the late-1950s. When the transfer of energy via power lines over long distances became possible, Hydro was able to commence construction of its first aluminium production plant in Karmøy, which was located on an island on the west coast of Norway. Karmøy was viewed as a favourable location for aluminium production activities because of the availability of cheap sea transport.

[9] In October 1999, the Dutch company Koninklijke Hoogovens merged with the British company British Steel, which has since been called 'Corus'. As the research took place before this merger, between 1960 and 1997, the old names Hoogovens and British Steel are used in this study.

[10] In the 1960s, it was practically impossible to buy large amounts of alumina or primary aluminium on the public market because of the monopolistic position of the six largest integrated aluminium companies: Alcan, Alcoa, Reynolds, Kaiser Aluminium, Pechiney and Aluisuisse.

Furthermore, the area had a surplus of labour at the time, and was very open and windy, which had the advantages of being more robust concerning environmental issues. In the 1960s and 1970s, the environmental problems with old aluminium production plants in Norway were very serious and were, in fact, the direct reason why the Norwegian Pollution Control Authorities[11] were established. The old Norwegian aluminium smelters had very large emissions, which gave rise to serious damage to the local environment, for example in Årdal, being located in a narrow valley, where the emissions destroyed the forests.[12]

The Karmøy plant was built on hydroelectric power. The plant obtained its energy supply from three lines. The power was produced at a power station in the area of Roldal/Suldal. Hydro owned that power station until 2000.[13] This power station was not enough for the total power consumption. Hydro also had *long-term energy contracts* with the government for the plant in Karmøy. Because Hydro did not have any aluminium production technology in 1967, it was looking for partnerships with other companies. Forces were combined in a joint venture with a relative small American company, Harvey Aluminium since Harvey did not have a market interest in Europe, Hydro acquired a free market position in Europe. As Harvey Aluminium used the Søderberg technology in their plant in Oregon, the drawings from that plant were used to design the Karmøy smelter.[14] Accordingly, the new Karmøy aluminium plant was then based on the Hall–Héroult process using Søderberg technology. In 1967, the Karmøy aluminium plant started with the production of 80,000 tons of aluminium per year.

9.2. The period 1970–1980

In 1970, the annual production capacity of Aldel increased to 96,000 tons of aluminium. At that time, the plans for the future were to double the capacity of Aldel, provided that the environmental problems could be solved. However, in the early 1970s, a surplus of aluminium became available on the markets, and the expansion of Aldel became less urgent. Furthermore, in 1971, Aluisuisse repelled its Aldel share due to the bad situation on the aluminium market, and Hoogovens and Billiton acquired full ownership of Aldel. After the energy crisis in 1973, many new aluminium producers arose worldwide, which bore down on the prices of aluminium. Furthermore, Aldel's competitive position was endangered by the expectation of a price increase of Dutch natural gas, and that the amount of gas assigned to Aldel would not be extended. Therefore, the interest in investing in aluminium decreased sharply, and it was decided in 1972 to stabilize Aldel's production capacity for the time being.

In 1979, Hydro took the decision for a *prebaked operation* in Karmøy because it recognized that the *Søderberg technology* had some environmental disadvantages. The prebaked technology used bigger reduction cells. Accordingly, it featured better productivity, lower investments and operating costs, lower energy consumption, and a higher current efficiency. Furthermore, the net carbon consumption of Søderberg cells was higher, producing more CO_2 per ton aluminium. Another problem with Søderberg cells was the relatively excessive emissions of polycyclic aromatic hydrocarbon (PAH). Hydro purchased the prebaked technology from Pechiney, being a technology leader in aluminium production technologies at that time.

9.3. The period 1980–1990

In the 1980s, a reorganization of the worldwide aluminium industry took place in response to the deteriorated aluminium market. The Dutch government went as far as wanting to investigate the possible consequences of closing down of Aldel. Due to the shortage of energy, the government had increased doubts about the returns of the use of natural gas in the aluminium smelter in Delfzijl. During the 1980s, the uncertainty continued about the survival of the aluminium activities at Aldel. Gradually, Hoogovens expanded its aluminium activities in the rolling sector, and when these activities were favourably developing, Hoogovens realized that aluminium could form a valuable reinforcement of its company. From 1986 onwards, Hoogovens strived to improve its aluminium activities by engaging in its own aluminium research. In 1987, Hoogovens took over the European interests of the aluminium company Kaiser, making Hoogovens part of the large aluminium producers in Europe.

In the 1980s, the natural gas supply to Aldel remained a problem. Due to the favourable conditions of natural gas delivery to Aldel, the Dutch State yearly missed about 75 million dollars on natural gas income. Hoogovens, however, strongly opposed the government's wish to break open the long-term energy contract with Aldel, pointing out the agreement concluded between the government and Aldel at the foundation

[11] The Norwegian Pollution Control Authority (SFT) is a Directorate under the Ministry of Environment, dealing with demands for permits, reports and annual schemes, and setting requirements for the 400 largest companies in Norway which have national effects on environmental pollution to air, water, noise and waste.

[12] Being situated in a valley was a disadvantage, because the emissions stayed longer in the valley, and therefore posed a persistent threat to vegetation.

[13] In fact, the Norwegian State owns the power stations. Hydro's power station returned to state ownership in the year 2000. Until then, Hydro had a concession, a legal right to operate the power station.

[14] If Hydro Aluminium had formed a joint venture with Pechiney in France, it probably would have implemented a prebaked plant.

of Aldel. The Minister insisted that from 1989 onwards, Aldel had to pay an electricity price corresponding with normal industrial large-scale consumers. Such a higher price was unacceptable for Hoogovens, because Aldel would then no longer be able to compete with other European smelters working with nuclear energy or specific governmental agreements. An agreement was finally reached in which Aldel had to pay an electricity price based on the price for industrial consumers from 1989 onwards, but that until the end of the original gas contract in 1998, a discount was applied to bridge the price gap. In the meantime, Hoogovens had to search for a permanent solution with cheaper energy sources. In the 1980s, Aldel had a production capacity of about 96,000 tons of primary aluminium and investments were made in the processing and treatment of secondary aluminium, because *secondary aluminium production* only required 5% of the energy compared to primary production. The installation of an oven to remelt the fabrication scrap brought the production capacity of Aldel to about 140,000 tons/year.

Since the merger of Hydro Aluminium with ÅSV (Årdal og Sunndal Verk) in 1986, being a very technology oriented company that developed a lot of process technology on its own, Hydro had a very good technology basis. Hydro improved and optimised its established aluminium smelter technology. The technological changes included gradual improvements on existing cell technology of the Hall–Héroult process, developed from primitive cells in the beginning into bigger and more advanced cells, without real new processes coming up in the Hall–Héroult technology.

Process-wise, one of the biggest inventions in primary aluminium production was point feeding, which was put in operation simultaneously by Alcoa and Pechiney in the late-1970s. Point feeding was a new means of controlling the cell through regulating the alumina feeding, so that the cells could be run at an optimum alumina percentage.[15] Elkem Norway has developed and sold anode top covering and *Søderberg point feeding technology* to Hydro Karmøy, and the emissions of PAH and PFCs have been reduced dramatically by 90% (almost comparable with prebaked technology).

Another process innovation was the *hooding of the cells with anode top covers*, driven by a combination of environmental concerns and the improvement of work hygiene. A collection system for gas, which could be scrubbed, was developed. Normally, the gases were first washed with (sea) water. Alcoa invented a process to scrub the gases with alumina feed: the emissions were reduced, and the expensive fluorine was recycled in the production system, this *dry scrubbing* also removing a small quantity of sulphur dioxide emissions.

9.4. The period 1990–1998

In the early 1990s, the aluminium industry was confronted worldwide with heavy losses. The growth in aluminium consumption decreased as a result of the economic recession. In addition, the extensive export of inexpensive aluminium from countries comprising the former Eastern Block threatened the existence of West-European aluminium smelters. In addition, the supply of aluminium on the world market increased due to new aluminium smelters in Canada and Brazil. All European aluminium smelters had big problems due to these dramatic developments. The global aluminium industry applied itself to a voluntary reduction in primary aluminium capacity.

Accordingly, Hoogovens voluntarily reduced its primary production capacity. From the mid-1990s onwards, the prospects for the aluminium industry became very optimistic once again, due to the disappearing overcapacity on the world market, increasing aluminium demands and increasing prices. In the meantime, Hoogovens studied the possibilities of obtaining its energy supply from the English electricity producer National Power, with the liberalization of the Dutch electricity market coming up. This company could possibly deliver electricity at a lower price than the Dutch electricity producers, which could probably enable the building of a new aluminium smelter in Delfzijl whilst remaining competitive. In the long term, a new smelter was a precondition to maintaining aluminium production at Delfzijl, as the existing smelter was very old-fashioned and highly energy consuming. By the end of 1994, Aldel produced about 150,000 tons of aluminium, of which 58,000 tons was secondary aluminium [57,58].

In early 1995, the future of Aldel was still uncertain because a new energy contract still had to be concluded by Hoogovens, the government and the Gasunie before 1998 [59]. The price of energy was therefore a decisive factor as to whether Hoogovens would invest 250 million dollars in a *new aluminium smelter* in Delfzijl. Hoogovens had a powerful instrument for placing pressure on the electricity sector in the form of its negotiations with electricity producers abroad. In February 1996, *a new long-term energy contract* for the supply of electricity for a favourable tariff was concluded between Hoogovens, the Dutch Gasunie and the government for a period of 10 years (until 2006). As a result of this agreement, Aldel would have to shut down its current primary aluminium smelter by 2006 [60,61]. As a result of this energy contract, Hoogovens planned to invest about US$80 million dollars in Aldel to renovate and modernize its machinery

[15] Point feeding also made it possible to measure when a cell was close to having an anode effect, thereby preventing the occurrence of an anode effect.

and to improve the working conditions, as no further investments had been made in Aldel in anticipation of the new energy contract since the early 1990s. In *the modernization program*, the electrolysis ovens would be thoroughly renovated by introducing *point-feeding technology*. In addition, environmental innovations and process control improvements would be carried out, which would lead to decreased emissions both into the air and the surface water. Aldel planned to install a new dry scrubbing system, a closed transport and transfer system for raw materials, and would dismantle the wet scrubbing system leading to discharges of rinsing water into the open sea [62,63]. The renovation project had to be finished at the end of 1999.

In March 1998, it was announced that the electrolysis department of Aldel's aluminium smelter did not have to be shut down at all costs, due to expectations of availability of sufficient cheap energy in 2006. Accordingly, the closure of Aldel's electrolysis plant was no longer an established fact. For the next few years, inexpensive energy would be transported from Norway and Iceland to Europe. In addition, the liberalization of the energy market could have a positive effect on the energy price, and the electrolysis plant would be renovated and modernized to such a large extent that in principle, the electrolysis could be used for much longer than up to 2006 [64].

During the 1990s, Hydro had followed the *developments on inert anodes*, trying to find out what it could do and at what scale. Researchers at Hydro's Research Centre and at Trondheim University worked on this radical technology at a relatively modest scale. Hydro did not see many breakthrough alternatives in aluminium production, although some promising ideas had been put forward on occasion. These ideas were checked, but none were deemed feasible.

There is a tremendous drive in the aluminium industry to reduce the costs of conventional aluminium production instead of developing alternative, radical technologies. Therefore, most of the innovative effort is put into achieving rational production, regarding size of the cell, the equipment used, and automation (i.e. process optimisation). These improvements require more engineering than research efforts. Hydro, for example, has developed its own, optimised, Hydro cell technology by focusing on improving the process, such as the bath conditions and the development of control systems [65]. When the aluminium company is already running at low energy and low carbon consumption, there is not much left to optimise in the existing process. Productivity and investment are the main costs, which depend on the size and number of cells. It is very costly to build new, very advanced cells. There is a 20 year investment lag in implementation of the most advanced cells, due to the high costs. When companies want to introduce radical new technology they have to increase their capacity, rather than improving existing capacity, because replacement will take about 40 years, being the depreciation time of an average aluminium smelter; this costs too much. When a new plant is built, the latest technology will be applied, but replacing is not a favourable option. So a big difference exists between the industrial average and the most advanced cells that could be used in aluminium electrolysis.

In 1997, the Karmøy aluminium production system consisted of an electrolytic reduction plant using both Søderberg and prebaked cells, and a cast house, making extrusion ingots. The plant got its power supply partly from Hydro's power stations[16] and partly via long-term energy agreements with Statkraft in Norway. Hydro's hydroelectric power stations represented about 30% of the annual production capacity in Hydro's plants. In early 1998, the Karmøy smelter was producing 270,000 tons of aluminium per year. The plant used 13,000 kW h/ton aluminium produced in the prebaked cells. The Søderberg cells used 16,000 kW h/ton aluminium. The energy costs and carbon costs of each represented some 15% of the total cost of aluminium production at the Karmøy plant. Following the expansion in 1997, Karmøy produced about 270,000 tons/year, making it one of the largest aluminium plants in Europe [66].

It is expected that Hydro's Søderberg plant will be closed and a new prebaked pot line will be built in the early 2000s due to the advantage posed by lower energy consumption and lower PAH emissions. In addition, productivity will be improved [67].

Table 3 gives an overview of the most important technology strategies the two companies followed in the period 1959–1998 (without the intention of being complete). The vertical axis provides, according to the conceptualisation in Section 3, the degree of radicalness of the technology strategies studied. This table shows that in both aluminium production systems, incremental, as well as more radical options have been selected as solutions.

10. Analysis of the two aluminium case studies

This section of the paper analyses the two case studies according to the mechanisms mentioned in Box 1.

10.1. Reverse salient and pressure leading to critical problems at the systems level

> "Above all, the future of Aldel in Delfzijl has been dependent on the possibility to maintain a competing energy price" [68].

[16] In fact, the power stations are owned by the Norwegian State. Hydro has the legal right to own them for a certain period. The existing concessions for the units are scheduled to terminate between 2007 and 2017. In the new agreement, these concessions for four of Hydro's hydropower production units are extended to 2046.

Table 3
Overview of the followed technology strategies and their radicalness

Radicalness technology strategy	Hydro Aluminium Karmøy (*Energy supply, Greenhouse gases*)	Aluminium Delfzijl (*Energy supply, Greenhouse gases*)
Incremental	New, long-term energy contract	New, long-term energy contract
	Point-feeding technology Søderberg	Point feeding
	Anode top covering	Modernization aluminium plant (e.g. environmental improvements)
In-process	Change from Søderberg to prebaked process	
Radical	Inert anode development	New electrolysis plant
		Secondary aluminium smelting

The main reverse salient or critical problem has been indicated in italics.

For both Aldel in The Netherlands and Hydro Aluminium in Norway, the most important precondition for starting up the aluminium smelter was the favourable long-term energy contract with the government. Accordingly, *energy supply* seems to be the most important slumbering reverse salient of both primary aluminium production systems, due to the fact that primary aluminium production is highly energy intensive.

The existence of Aldel is highly dependent upon the continuation of long-term, inexpensive energy contracts with the Dutch government. The prolongation of these energy contracts is increasingly becoming a problem for Aldel, also because of increasing environmental pressure, especially from local environmental groups, which forces Aldel to rethink its primary production activities and to consider secondary aluminium production. Aldel still has an energy contract until 2006, but it is uncertain whether it will be renewed. For Aldel, energy supply will probably become a real critical problem in the near future, making the survival of Aldel's primary aluminium production system questionable.[17]

Hydro Aluminium owns some hydroelectric power stations but still has to negotiate its long-term energy contracts with the Norwegian government. The main debates in Norway are about the energy price and where to obtain the extra power needed. In 1997, all the aluminium smelters in Norway were in negotiation with the government for future energy contracts. Norsk Hydro and Statkraft entered into a comprehensive long-term energy agreement extending energy supplies to Hydro until 2020.

Another slumbering reverse salient for the two aluminium production systems is the emission of *greenhouse gases* generated during primary aluminium production. Besides CO_2, heavily coupled to the use of fossil fuel based energy and carbon resources, the greenhouse gases CF_4 and C_2F_6 (perfluorocarbons), which are very potent, are emitted during primary aluminium production. Environmental pressure on aluminium smelters will therefore likely increase as a result of the outcomes of the Kyoto protocol and other international climate change agreements between industries and authorities.

In summary, for Aldel, control of energy supply via a long-term energy agreement was, and still is, the main problem threatening its continued existence. For Hydro, no critical problem has occurred so far, but the slumbering reverse salient of control of energy supply in the future and probably greenhouse gas emissions are waiting in the wings.

10.2. Translation of critical problems into potential solution directions

> "All industry needs to be pushed forward by outsiders. Today, many industrial leaders in Norway take the view that it is good for them, as industries that there are organizations and activities outside of them, that keep them alert … External pressure is necessary to get the right thinking for long-term solutions" [69].

Both Aldel and Hydro Aluminium wanted to become less dependent on energy supply. First, both companies tried to postpone the potential energy crisis by negotiating new, long-term energy contracts with their authorities. The companies also considered various technological alternatives to reduce their dependency on energy to some extent. The amount of energy consumed when remelting or recycling collected aluminium scrap is only about 5% of the energy needed to produce the corresponding amount of primary aluminium. Both Aldel and Hydro Aluminium were therefore increasingly involved in secondary aluminium remelt and recycling operations. Furthermore, Hydro implemented new technologies in its primary production process that consume less energy. For example, it selected the prebaked technology instead of Søderberg technology during the plant expansion that took place in 1979. Furthermore, Hydro is also following the developments in inert anode technology, which would consume only a little energy compared to the established aluminium smelting process.

Aldel began secondary smelting of aluminium in addition to its primary activities in order to become less dependent on its energy supply. Furthermore, Aldel considered modernization of its existing primary aluminium production plant in order to improve (energy) efficiency and productivity and to decrease its environmental burden.

In 1995, Hydro Aluminium obtained its new energy contract for 20 years' primary aluminium production.

[17] It is, however, uncertain how the energy situation will be in 2006, considering the current liberalization of the energy markets, which could probably make cheap energy supply possible again.

At the same time, the Dutch authorities decided that Aldel would not be given a new energy contract from 2006 onwards. Its primary aluminium production will likely cease when the current energy contract ends in 2006. If restrictions on greenhouse gases become more severe in the future, due to international agreements, the primary aluminium industry will have to look seriously into technological alternatives. Hydro's developed point-feeding technology for Søderberg cells reduces specific greenhouse emissions of CF_4 and C_2F_6. In addition, the change from Søderberg to prebaked technology also decreases the emissions of fluoride compounds to some extent.

Following the critical problems and solutions pursued by Hydro, a shift in problem definition could be detected from a situation with high availability of energy in the form of hydroelectric power, to a situation with re-negotiation of the energy agreements with the government, and finding technical solutions to reduce energy consumption and greenhouse gas emissions, such as PFCs and CO_2.

10.3. Structure of the technology network and interactions of involved actors

> "Cooperation between the aluminium industry, research organizations, such as the Norwegian Research Board and the authorities such as the Norwegian Pollution Control Authority SFT, is necessary to make sure that we develop projects together that have a long-term development perspective … " [70].

Aldel has no research facilities itself, only a small troubleshooting department to solve its day-to-day production problems. Since it is a part of Hoogovens, Aldel could make use of the research facilities at Hoogovens' Corporate Research Laboratory. Hoogovens, however, is traditionally a steel maker, which has only put considerable effort into aluminium research activities since 1986. Compared to Hydro Aluminium, Hoogovens has no long-lasting history in aluminium research. This is probably the reason why no extended aluminium research and technology network was available within Hoogovens for a long time.

Hydro Aluminium has an extensive research and technology network at its disposal for exploring various technological alternatives. There is an Aluminium Research Center in Ardall, and a Corporate Research Laboratory in Porsgrunn. Furthermore, Norsk Hydro has a long historical tradition in primary aluminium production, having various wholly-owned primary smelters. In addition to a large internal, multi-materials oriented R&D network, which has enabled it to produce many other products such as agrochemicals, PVC, magnesium, Norsk Hydro also has close contacts with universities and technological institutes in Norway and abroad. The interactions with these external actors seemed to be very important for the process developments within Hydro Aluminium itself and for the joint projects on inert anode technology development. In general, the aluminium industry is hesitating to invest heavily in inert anode technology because it is risky and unproven. Their established aluminium production technology is working, and engineers are trained to prolonging its longevity. The entire knowledge infrastructure is mainly based on established aluminium reduction technology.

10.4. The radicalness and implementation of the chosen technology strategies

> "All 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" [71].

Regarding actual implementation, financial assets and high capital investments appear to play an important role in aluminium production systems. Enormous capital investments are required to construct a new aluminium plant using the latest technology. Such high investment demands long investments terms. Actual implementation of a new secondary aluminium smelting option at Aldel depends heavily upon the question of whether or not it is going to cease its primary activities by 2006. This might be dependent on the availability of other inexpensive energy suppliers. Accordingly, a high degree of organizational embeddedness seems to complicate its implementation to a large extent. Aldel also implemented some incremental and in-process innovations in its established aluminium production system, such as improved cleaning installations and the introduction of point-feeding technology in the aluminium production process.

For Hydro Aluminium, new long-term energy agreements have been forged between Hydro and Statkraft until 2020. Various in-process improvements to the existing aluminium production process have been carried out in order to reduce energy consumption and emissions of greenhouse gases, such as the change from Søderberg to prebaked cells, the implementation of point-feeding technology at the prebaked as well as the Søderberg cells, and anode top covering. The radical inert anode development has been followed by Hydro, but this technology has not yet been further developed or implemented.

Fig. 2 provides an overview of the radicalness and degree of implementation of the various technology strategies studied. The 'technology box' includes the developments, which are still in the pipeline.

It has been observed that the achievement of new long-term energy contracts does not stimulate Hydro

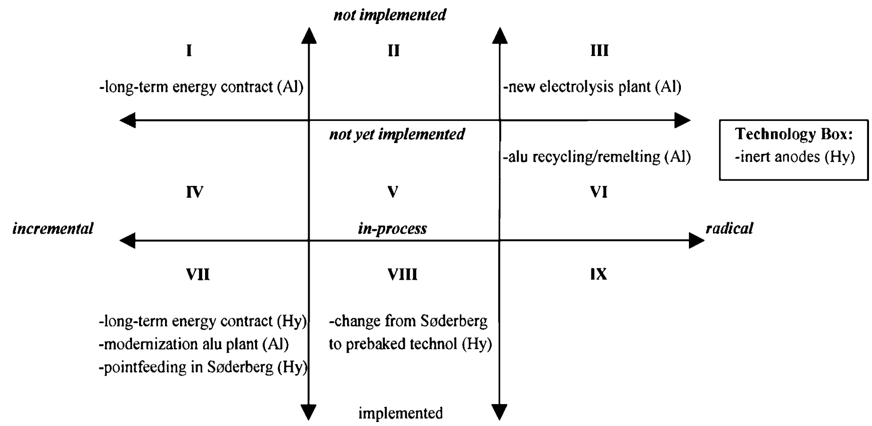

Fig. 2. The radicalness and implementation degree of the various technology strategies studied in aluminium production. Hy = technology strategies of Hydro Aluminium; Al = technology strategies of Aldel. The 'technology box' includes the developments, which are still in the pipeline.

and Aldel to further develop new production alternatives, such as inert anode technology, which would make them less dependent on energy in their primary aluminium production process over the long term. An important reason for the relative reluctance of the studied aluminium production firms to largely change their primary production process could be that the entire aluminium industry has been using the established Hall–Héroult process to produce aluminium for more than hundred years. This primary production process has been made highly efficient throughout the years. Other primary aluminium production processes, based on other process principles, have barely been developed, the Alcoa and the carbothermic reduction process being the only exceptions, and not implemented at all. It seems that the aluminium industry as a whole has been locked into its own Hall–Héroult production paradigm. This makes it very difficult to research radical new aluminium processes based on another production principle, because the research tradition has not become accustomed to doing so.

11. Concluding remarks

The main process available to produce aluminium, the Hall–Héroult process, is more than 100 years old and is still applied in all primary aluminium smelters. It follows that not many radical process innovations have been actually implemented in the two studied primary aluminium production systems. Their research activities have not traditionally been particularly process-oriented. The case studies showed that the availability of a research and technology network, featuring numerous external interactions, and including various knowledge fields, is vital for the development of new, more radical technology strategies. In addition, the internal research networks should be stabilized to some extent, or, in other words, there should be a research tradition in aluminium within the company.

As the aluminium industry is highly capital intensive, with very long depreciation times in its established production lines (often more than 40 years), the implementation of radical process innovations is difficult. Investment and expansion decisions therefore must be made well in advance. New technological options need to be intertwined within the existing aluminium production system because of the very high costs associated with the new infrastructure, harbour, alumina storage facilities, administration, that must be put in place. The exceptions are expansion decisions of the present companies. Only then can the implementation of entirely new radical concepts be possible.

It has been argued that the awareness of an actual critical problem, due to increased external environmental pressure upon the aluminium production system, is a major driver for the development of radical innovations in the aluminium industry. Interactions with firm-external actors are also important. The high degree of technical embeddedness and vested organizational linkages, amongst others in long-term contracts, between the suppliers and customers of the aluminium production system seem to complicate the implementation of radical technologies. New, radical technology strategies are often being implemented when firms are expanding.

Policy instruments should therefore be focused on the sensitivity of large aluminium firms to external pressure. Additionally, firm management should reinforce existing, firm-internal research and technology networks by including a high density of heterogeneous specialists. More outsiders should be enrolled in these technology networks to bring in knowledge and experience about new, radical concepts.

Finally, governments should tune their technology policy on business-expanding programs. After all, this study has found that production expansion often accompanies new capital investments and implementation of more efficient new technologies. Such technologies very often have a positive effect on the environmental efficiency of the total production system. Governments could stimulate the implementation of radical innovations in aluminium production in the following two ways: first, via intervening in the large established aluminium firms with technology subsidies or technology development credits for the actual implementation of risky unproven radical technologies. Second, governments could invest in new small aluminium firms to induce radical changes. These small aluminium firms often lack the necessary resources, process knowledge and experience to pilot-scale the developments, but could likely fulfill a triggering role towards the large firms picking up their new ideas.

To conclude, in the words of a senior vice president of corporate research and development at a large integrated metals producing firm: "New technologies seldom emerge. Incremental improvements are made continuously with good success, new ideas are presented frequently, but commercially significant quantum leaps are rare. However, important development has taken place during the last few decades in the metals producing industry. The environmental and hygienic pressures have become a driving force for the development of technologies, although vigorous competition remains an important driver, as well as aspects related to energy."

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