Innovation and production in the Norwegian aluminium industry[1]

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Abstract

The innovation and production system of the Norwegian primary aluminium industry has changed during the last 100 years. In the first phase from 1908-1945, the locus of innovation resided first and foremost abroad. In the second phase (1945-1986) the Norwegian aluminium industry gradually created a more autonomous path regarding innovation and production. The Norwegian Government created supporting institutions, and in combination company strategies, this laid foundations for the National champions Hydro and Elektrokjemisk to enter. The third phase (1986-) is first and foremost associated with the creation of Norwegian vertically integrated aluminium companies and horizontal expansion marked by the merger of ÅSV and Norsk Hydro (1986).

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Paths of innovation and production

The emergence of the process industries in the early 20th century Norway has been analysed as a process of "path creation" in the Norwegian innovation system (NIS) that included the entry of new social groups, such as scientists, engineers and managers, into prominent economic roles (Wicken 2007). The production of aluminium in Norway, one of the most economically and technologically of these process industries, began in 1908, initiated by foreign industrialists who wanted to take advantage of Norway's location, being relatively close to European markets, having infrastructure and political stability, and most importantly, access to comparatively inexpensive hydro power. However, there are certainly other elements that help explain why Norway has become a substantial producer and exporter of primary aluminium. The companies have built large scale R&D laboratories at their aluminium smelters; research institutes and universities have entered the innovation system and developed strong research capabilities in aluminium, functioning as important recruitment pools for the aluminium companies and the research institute sector; R&D collaborations between firms and institutes have gradually emerged; and supporting industrial and regional policies have been set up by the Norwegian Government. Earlier studies of this industry have described it as one of the major clusters in Norway with relatively cheap energy supply and high competence (see Reve 1992, Svendsen and Rikter-Svendsen 1992).[2]

This paper describes the main drivers of innovation and production in aluminium from a contemporary and a historical point of view. It draws on various sources of evidence and ideas (Ragin 1994: 56-76). For example, we draw upon interviews with present and former directors; plant managers and engineers; and people who represent industry federations. We also use public and company reports and basic statistics. Other sources include secondary literature such as scientific articles and books, newspapers and magazines.

In the aluminium industry, innovation is intimately linked to production, which calls for a focus not only on the production system as well as the innovation system. The industry's structure and performance are influenced by the co-evolution of actors (e.g. firms, organisations, individuals) and networks[3] (e.g. innovation and R&D collaboration), technologies and knowledge (technologies and knowledge applied for the innovations and in the production process of primary aluminium), and institutions (e.g. laws, regulations, standards, norms) (Malerba 2002). Furthermore, this co-evolution takes place both nationally and abroad. For example, aluminium plants in Norway have historically depended on foreign companies, organisations and institutions in order to innovate, produce and survive. This paper accordingly presents an international perspective on the production and innovation systems for Norwegian aluminium. The character of these linkages within the aluminium industry has changed through time.

Production, vertical chains, and cost structure

The production of aluminium involves technical processes that constitute a vertical chain that goes from "upstream" to "downstream" activities. The primary aluminium smelters are vertically linked to processes that take place "upstream," e.g., mining and alumina refining where bauxite is converted into alumina by the Bayer (refining) process. Primary smelting is when alumina is processed into primary metal by the Hall-Héroult process. The stages "downstream" include the production of semi-fabricated goods such as sheet, foil, wire, rod, and bar, and the end-product stage, which uses aluminium to manufacture products that range from aircraft, automobiles, and ships to packaging. The smelting stage itself spans both upstream and downstream categories. Although most primary smelters have semi-fabrication

plants attached to them, smelting and fabricating are quite distinct processes. Smelting also includes the creation of alloys, which give different properties to the metal (Stuckey 1983).

This paper focuses on primary aluminium smelting at Norwegian plants, which is as mentioned very different from the production of alumina or the production of aluminium products. Some of the primary plants have been active longer than 60 years. There are 250 primary aluminium smelters in 42 countries worldwide (Altech Innovative 2006). In 1900 the world's total annual primary aluminium output was about 8 thousand metric tonnes, while in 1946, following wartime mobilization, annual production was 681 thousand metric tonnes. The reported numbers for 2006 were 23 866 thousand metric tonnes (IAI Statistics 2007). Aluminium competes in industrial applications with other materials such as wood, paper glass, plastics, steel, copper, and other light metals. Over 90 percent of the Norwegian production of aluminium is exported, accounting for nearly six percent of all Norwegian export commodities in 2005. Norway is the fifth largest aluminium exporter in the world (UNCTAD/WTO: 2006) and aluminium exports account for a larger share of Norwegian exports than fish (4, 3 percent) (Statistics Norway: 2006, SITC). There are 7 aluminium smelters in Norway, operated by Hydro Aluminium, Elkem Aluminium ANS, and Sør-Norge Aluminium (Sør-Al)[4]. Presently, Elkem Aluminium ANS is owned by the Norwegian company Orkla ASA and Norsk Alcoa, a subsidiary of Aluminum Company of America (Alcoa). Sør-Al is owned by Hydro Aluminium and Aluminum Limited of Canada (Alcan). Hydro Aluminium operates Sunndal, Karmøy, Årdal and Høyanger; Elkem operates Lista and Mosjøen, and Sør-Al operates at Husnes. The 7 Norwegian smelters produced about 1.4 million metric tonnes in 2005. Figure 1 shows the production of primary aluminium at these smelters.

[FIGURE 1 ABOUT HERE]

The price of aluminium smelters' output fluctuates widely, and the competitiveness of smelters is determined primarily by their operating costs. Average costs for "representative" smelters in the global industry are influenced mainly by the costs of alumina (40% of average costs) and power (26%), followed by carbon (10%), labour (7%) casthouse (4%), where the metal is taken to a holding furnace, often blended to an alloy specification, then cleaned and generally cast. The remaining "other" costs (13%) include elements such as transport, administration, logistics etc. A central driver of innovation in primary aluminium production is cost reduction through process innovation aimed at reducing energy costs, capital costs, and at improving environmental performance by reducing/eliminating air emissions. In addition, plants seek to improve the purity of the metal and to add alloys in order to obtain different qualities and properties for different uses. The world average production cost in 2005 was 1375 USD per tonne of produced primary aluminium (CRU 2005). In Norway, alumina and carbon prices are related to world market prices, while energy is dependent on regional and national price mechanisms. Agreements with the Norwegian State on energy prises has benefited (some would say subsidised) the aluminium industry, which has enabled long term investments, hence large sunk costs in production capacity. Similar polices have been pursued in other industrialised countries, but during the last decades the companies have invested in "energy rich" parts of the world, often in developing countries. We will return to this is section 5.

[TABLE 1 ABOUT HERE]

The world smelters' operating costs vary from smelter to smelter and are heavily influenced by the price of energy, which differs greatly from region to region. Other important influences on production costs are establishment scale and the vintage of plant-level technology, since old technology packages normally are less efficient than new technology packages. Relatively low factor costs are essential to smelter competitiveness. Important cost-reducing process innovations include improvements in the quality of the raw materials, and innovations in production machinery (e.g. cells, anodes, cathodes, transmission lines for power, computer control). These and other process innovations may affect or be affected by how a smelter organises work or the competence of the engineers and operators at the plants (how technology is used), which in turn are affected by the R&D and innovation networks of firms (e.g. R&D institutes and educational organisations).[5] Innovation and efficient technology adoption are essential to competitiveness, and at least some of the earliest entrants in the Norwegian aluminium industry have been able survive by being innovative, combined with institutional support in terms of energy supply, and access across the value chain such as long term alumina supplies from alumina producers, and more recently integration downstream to aluminium products.

Aluminium has been produced commercially for roughly 150 years. Until the end of the 19th century, aluminium was produced at production sites located in Europe and was regarded as a precious metal, because of its very high production costs. The market was small, competing with metals like gold and silver. From 1855-1885 about 40 000 kilos of aluminium were produced, mostly in England and France (Kollenborg 1962: 11, Edwards 1930: 6). At the end of the 19th century however, a radical technological shift occurred that eventually laid the foundation for the Norwegian aluminium industry. We need to account for these processes in order to fully grasp the Norwegian case.

Global sources of aluminium innovation and production (1908-1945)

The development of dynamo-electric machines and their application to metallurgical processes in combination with two new processes, electrolysis and the Bayer process, revolutionised the aluminium industry in the late 19th century. Paul Louis Toussaint Héroult (France) and Charles Martin Hall (USA), unaware of each other's work, each invented a new electrolytic process in 1886. Their processes dissolved aluminium oxide (alumina) in a bath of molten cryolite and passed a powerful electric current through it, resulting in a deposit of molten aluminium at the bottom of the bath. These processes were patented, and only a handful of companies acquired the patents. Innovations in minerals extraction also affected the aluminium industry by making raw materials cheaper and more accessible. One process developed by Karl Joseph Bayer (Germany) between 1887 and 1892 improved the extraction of alumina from the bauxite ore (Edwards: 1930). Similar to the Hall- Héroult patent, it was important to have the rights to the Bayer patent and acquire bauxite deposits in order to become self-sufficient enterprises upstream – which were of crucial importance at the primary phases of production (Smith 1988: 99-101).

In 1889, aluminium production was begun by Hall and some American industrialists, who founded the Pittsburgh Reduction Company in the US (renamed the Aluminum Company of America - Alcoa in 1907). The cheapness of the electrolysis process displaced the European smelters using the old production process. In the face of rising wage demands of labour, the US company sought new production sites with cheap power (Graham, 1982:16). In the 1890s, Alcoa moved production to New Kensington, outside of Pittsburgh, for the natural gas supplies, and to Niagara Falls, to take advantage of the electricity provided by the Niagara River Power Company. Inexpensive energy, combined with process innovations, made aluminium prices fall swiftly, making aluminium competitive with other metals. The process

innovations developed by Hall (in Alcoa) and by Heroult (in Neuhausen, Europe) improved the current efficiency of the cells and the electrolyte for the cells, which in turn required innovation within the carbon electrode technology in order to keep phase with the expanding size of cells (which are the "pots" in which aluminium is produced) and increasing cell amperage (Peterson and Miller 1986). The larger the cell, the more efficient the production processes. Alcoa purchased equity in the emerging US automobile industry and electricity transmission firms, and, developed a vertically integrated structure that included fabrication operations and control over bauxite deposits (Graham 1982:16).

Similar strategies of innovation and integration were pursued by the European companies. After the radical technological shift that took place around 1890, four companies managed to enter the aluminium industry based on the Hall-Héroult patent. Héroult cells were first operated commercially at Neuhausen in 1888 by the Swiss company *Aluminiumindustrie A.G* (AIAG), where Heroult had taken his smelting process in order to take advantage of the potential hydro power in this area. AIAG was the first mover and became the largest company in Europe, with smelters in Italy, Norway, Spain, and Great Britain (Tresselt: 1968, Graham: 1982, Holloway: 1988). The French company, Société Electrometallurgique Francaise (Froges), was founded by Héroult in 1889 with the financial support of AIAG. Froges later merged with Pechiney[6] (Rinde 1996: 5, Tresselt 1968: 7-8, Singer et al 1958: 93). In UK, the British Aluminium Co Ltd (BACO) was formed in 1894, acquiring the British and colonial rights for the Bayer and Héroult patents for alumina extraction and aluminium reduction (Cailluet: 2001).

When Héroult's patent expired in Europe in 1906, seven new firms began to construct plant facilities, but by 1910, three had been purchased by larger established companies. The

remaining four remained independent and relatively small (Wallace 1937: 38-39). In response to the resulting price competition, Alcoa (US) and the largest European companies established international bauxite-aluminium cartels and acquired most of the new entrants, thus regulating price, quantities of production of aluminium and bauxite supplies. In the US, Alcoa managed to secure an additional three years of patent protection beyond the original expiration date of 1906, which combined with acquisitions, exploration activities, purchases of riparian rights, bauxite and hydroelectric resources, established the firm as a monopolist within the U.S.for half a century (Smith 1988, Barham 1994).

Until the First World War, Alcoa, Alcan[7], AIAG, Pechiney, and BACO dominated the global aluminium industry. With the expiration of their patents on electrolysis, these firms' dominance[8] rested on their development and control of a system of technologies and knowledge, networks and institutions. They had learned how to dominate the various phases from bauxite to aluminium to manufacture and distribute semi-finished and finished products through large-scale growth and vertical integration, combining these strategies with in-house research and engineering capabilities (Smith 1988: 40-42, Le Roux 2000). In sum, patents, technological monopoly, economies of scale, capital intensiveness, cartels, and vertical integration provided important barriers to entry. The resulting market power of established firms had substantial effects on innovation and production in the first phase in the Norwegian aluminium industry.

An important precondition for the establishment of the Norwegian aluminium industry at the beginning of the 20th century was the construction of the infrastructure for hydro power plants to be used by foreign companies (Rinde 1996: 9-10). Hydro power became accessible at relatively low cost due to overinvestment in the hydropower sector. Other country-specific factors such as domestic demand and related industries up and downstream were nearly

absent. Other than considerable competence in hydropower development and technology, Norway thus lacked the knowledge base and the institutions that could support entry by domestic firms into the aluminium industry (Svendsen and Rikter Svendsen, 1992: 2-11). As early as 1906, during the construction of the first Norwegian aluminium plant, an influential engineer at Hydro expressed concern that the Norwegian aluminium industry would: “become controlled by a cartel who disposes the bauxite” (Gjølme Andersen and Yttri 1997: 58). At that time, Hydro sought to enter the aluminium industry, but its lack of access to the raw materials led Hydro’s consultants to recommend that the company not carry out the aluminium project (Gjølme Andersen and Yttri 1997: 58-60).

International events and processes in the aluminium industry were the key factors in the foundation of the Norwegian aluminium industry, for example: the Norwegian plants became controlled by cartels that were controlled by a few large foreign companies. More importantly, the Norwegian producers became heavily dependent on these companies for knowledge, technology and access to markets. Bauxite mining, alumina refining, and electrolysis were technically complex processes in which Norwegian firms had little knowledge and no experience (Rinde 1996: 15). Norwegian actors lacked organisational resources and skills, entrepreneurial competence, venture capital, access to markets and distribution channels, knowledge, and technology, which helps explain why the development of the first Norwegian aluminium smelters took place under foreign ownership. Table 2 shows an overview of the operating companies and their ownership from 1908 to present.

[TABLE 2 ABOUT HERE]

Stongfjorden aluminium, the first aluminium plant in Norway, was initiated, built, and run by the British Aluminium Company (BACO) which acquired riparian rights in Stongfjorden from the Ministry of Domestic Affairs and began operation of its smelters in 1908 (Tresselt 1968: 8-9). In 1945 (see Table 2) the plant halted production because of a lack of bauxite supplies (Kollenborg 1962: 110). Another British company, the Anglo Norwegian Company built the second plant, Vigeland Brug, which started production in 1908. The company was based in London, using Héroult's patent. Vigeland Brug was planned by a Suisse engineer, and its turbines, ironworks, machinery, and smelters, as well as the power station, were supplied by Suisse subsidiaries. Foreign engineers were in charge of plant management, and alumina was imported from the bauxite company Giulini, which did not participate in the international bauxite-aluminium cartel. The fall in the price of aluminium from £77 per metric ton in 1910 to £53 in 1911, combined with technical problems in the smelters, a malfunctioning sales organisation, and labor unrest, led to heavy indebtedness and eventually, the acquisition of the plant by BACO in 1912 (Krogstad 1999: 15-85, see also Tresselt: 1968: 8-9). [9]

The Høyanger plant was completed in 1917 by Actieselskapet Norsk Aluminium Company (NACO), and was the third Norwegian aluminium plant. Høyanger was initiated as a Norwegian project, relying primarily on Norwegian actors and capital (Gjølme Andersen and Yttri 1997: 58). NACO's strategy from the beginning was to establish a vertically integrated aluminium company. Bauxite supplies came from France, through NACO's subsidiary, Société Anonyme des Bauxites et Alumines Province, which operated bauxite mines. A plant for the manufacturing of aluminium products (such as cans), Nordisk Aluminium (at Holmestrand), began production in 1920. But NACO's staff had little experience in the aluminium industry, and it was nearly impossible to hire staff with sufficient knowledge about

alumina refining and aluminium smelting in Norway. Most of the firm's machinery was imported from the US, and its engineers and workers were hired from Europe and the US (Fasting 1966). NACO's bauxite-mining project collapsed shortly after the firm's foundation, because French industrial interests blocked the firm's access to bauxite because of its status as a firm from a neutral nation during WWI. NACO also was crippled by problems in building and running the alumina refinery in France, which eventually lead to its bankruptcy. Alcoa acquired NACO in 1923, and gained control over the alumina refinery (Fasting 1965: 109-141).

The French company Pechiney founded Det Norske Nitridaktieselekap (DNN) together with other French investors and the Norwegian owned Elektrokjemisk in 1912. Elektrokjemisk had been formed in 1904, and was an entrepreneurial company in industries related to hydro power and metals (Sogner 2003). DNN originally intended to produce nitrate, but Elektrokjemisk sold its DNN share to SGN in 1913, (Kollenborg 1962) and Pechiney built aluminium smelters instead, precluding Elektrokjemisk's ability to become a rival in the aluminium industry. Primary aluminium plants were built at Eydehavn, where production started in 1914, and in Tyssedal, which opened in 1916. These two plants made DNN the largest manufacturer of aluminium in Norway until 1947 (Tresselt 1968: 9-10, Rinde 1996: 7). Pechiney financed the development projects; and alumina oxide was imported from Pechiney's plants in France (Kollenborg 1962). Another plant – Haugvik Smelteverk -- was built in 1926 in Glomfjord by the British International Aluminium Company Ltd. In 1932, shares of the company were bought by a cartel consisting of Alcan Pechiney and WAV, AIAG and BACO.

Elektrokjemsisk controlled the patents on the Söderberg smelting technology, which was widely used in the metals industry and which became one of the two leading technologies in the world primary aluminium industry from the beginning of the mid-1930s. The Söderberg technology uses a continuous anode, which is delivered to the cell in the form of a paste, and which bakes in the cell itself. The other smelting technology, the "pre-bake technology," uses multiple anodes in each cell that are pre-baked in a separate facility and attached to rods that suspend the anodes in the cell. New anodes are exchanged for spent anodes, which are recycled into new anodes (IAI 2006). In 1950, the Söderberg technology accounted for about 50% of the global primary aluminium production capacity, with prebake accounting for the other 50% (Petersen 1953: 211). Although the Söderberg technology had a major impact in the world aluminium industry from 1935 on, little, if any institutional support existed for Norwegian firms to enter the the primary aluminium industry. The multinationals that dominated Norwegian aluminium production also controlled access to bauxite and downstream distribution. Since Elektrokjemisk had by the 1930s become a specialised technology supplier, providing global aluminium producers and other metals companies with the Söderberg smelting technology, entering into aluminium production would have created conflicts with the firm's customers (especially Alcoa) (Sogner 2003: 127-128, Petersen 1953: 79-94). Elektrokjemisk also did not have the finance, networks or market access to produce and sell aluminium. The early international entrants had maintained their innovative advantages while at the same time controlling production and sales. Even though the patents on electrolysis had expired in the early 20th century, these early entrants further developed their technology, expanded production capacity, and integrated vertically. But technology and patents were not the only barriers; the cartels organised by the industrial leaders put institutional constraints on Norway. These factors all discouraged entry by Norwegian or other firms into the aluminium industry during the pre-1945 period. Although a significant

knowledge base in primary aluminium production had developed in Norway during the 1908-1945 period (e.g. Elektrokjemisk's Söderberg technology) (Wulff 1992), production and distribution remained under the control of companies like BACO, Alcoa, Alcan and Pechiney. The explosion in demand for aluminium during WWII led to vast investments in the Norwegian metals industry that greatly expanded production capacity, and created the preconditions for the growth of a more autonomous Norwegian aluminium industry after 1945.

Creating a path of autonomous development (1945-1986)

Wars often affect the evolution of industries. Its occupation of Norway meant that Germany acquired control of the Norwegian aluminium industry. Hermann Göring, head of the Luftwaffe, needed aluminium for military aircraft production, and he established the Nordische Aluminium Gesellschaft (Nordag), financed by Germany, and supported technologically by the German company IG Farben. Norsk Hydro, IG Farben and Nordag collaborated through a sister company of Nordag, AS Nordisk Lettmetall, in developing the Norwegian aluminium industry (Gjølme Andersen 2005: 365-398). Germany invested 8-9 billion NOK (1997 prices) in R&D, aluminium plants, one alumina plant, and hydropower plants (Rinde 1997: 77-79). Wartime requirements also produced a significant expansion in US aluminum production capacity and weakened the long-established monopoly within the US domestic industry, since Alcoa could not meet the allied demand for aluminium. The Federal Government financed the necessary investments in production capacity, and in 1945, the War Surplus Property Board sold the Government-owned plants to independent firms, forcing Alcoa to face competition from integrated domestic producers of aluminium such as Kaiser (1946) and Reynolds (a metal company since 1928) (Smith 1988: 192). The new companies needed more production capacity, and looked at locations in Norway.

The wartime mobilization and demobilization policies in Germany and in the US illustrate not only the powerful influence of global flows of technology and capital, but even competition policy and war strategies on Norway's innovation system in aluminium. The post-war restructuring of Norway's aluminium industry required change in the international structure of the industry. But domestic postwar developments also affected the involvement of the Norwegian State in the aluminium industry after 1945: In the aftermath of the war the Norwegian government took over all enemy property, finished the German aluminium project at Årdal (1948), and at Sunndalsøra (1954), and established the state-owned company Årdal og Sunndal Verk (ÅSV). In Norway, it was a practical policy, a long term economic strategy with an ideological rationale of the Norwegian Labour Party to support heavy industry which included the use of water power. Indeed, there was a motive of increasing the production and adding more value in Norwegian industries; and the government wanted to develop the export oriented industries (Byrkjeland and Langeland 2000: 27-35). Furthermore, the plant at Sunndalsøra benefited not only from Norwegian State intervention, but also the fact that Economic Cooperation Administration (ECA) in the US that administered the Marshall Plan managed to raise funding for Sunndalsøra when the Korean War broke out. The US government wanted to ensure its access to aluminium during wartime (Ingulstad 2006).

Alumina supply has always been a major concern of primary aluminium producers. In 1947 and onwards, ÅSV managed to acquire a long-term supply of alumina through agreements with Alcan and Alcoa, who in return received a share of the primary aluminium that ÅSV produced, something that they needed for their fabrication activities in Europe. ÅSV also got financial loans from these companies in order to increase its smelting capacity. During the period of strong postwar demand for primary aluminium that lasted until 1958, ÅSV

increased production and aluminium sales significantly. Profits were reinvested in expanded production capacity and better cell technology and infrastructure to further increase smelting capacity. However, the company did not build up competence outside electrolysis. Neither did they buy shares in the bauxite industry or collaborate with other companies to build oxide plants. There were possibilities for vertical downstream integration in collaboration with the American aluminium company Harvey and for upstream integration into bauxite in Yugoslavia (Rinde 1996: 36-44). However, ÅSV did not find the bauxite mines to be an attractive investment (Gøte 2001: 20-21). Equally important was the fundamental strategy for ÅSV, which focused on 'concentrating labour and capital on electrolysis', in which Norway had 'exceptional natural conditions', these were activities that had given the company economic success and the firm's state ownership made its strategic concentration on Norway politically important (Rinde 1996: 43).

Beginning in 1953, ÅSV entered into research collaborations with researchers at the Norwegian School of Science and Technology (NTH), which was supported by the Research Council for Scientific and Industrial Research (NTNF). One of the projects at NTH, "the theory of aluminium electrolysis" was initiated in 1953 and proceeded until the late 1980s (Gulowsen 2000: 144). Much of this early collaborative R&D focused on improving the efficiency at ÅSV's plants, which was rather low by international standards. In 1965, the managers at ÅSV found that during 1955-1962, the productivity of ÅSV was 33 – 45% of the productivity level of US plants. In 1965, average production per employee in US aluminium smelters was 130 tonnes pr employee, while the number for ÅSV was 55 tonnes (Myrvang 2000: 77).

From 1945 until the late 1970s, the world aluminium industry was dominated by oligopolies represented by the “Big Six”: Alcoa, Alcan, Reynolds, and Kaiser in the US, and Pechiney and Alusuisse in Europe (Holloway: 1988). Essential for the entry of Norwegian firms where Norwegian institutions. ÅSV, Elektrokjemisk, and Norsk Hydro and other large Norwegian companies in the process industries benefited from governmental industrial policies. Governmental policies gave incentives (e.g. tax breaks and long term power supply) for investment by domestic firms, but also foreign firms in the aluminium industry. The Norwegian Government set up a committee for industrial finance in 1959 to attract foreign capital into Norway, and launched a program (1959-1960) to increase the production of aluminium rapidly (Johannesen et al 2005: 233-256). Some of the policy tools used to achieve this goal provided great advantages to Elektrokjemisk. The company had large surpluses from its ferrosilicon and mining operations that the new tax regulations enabled the firm to reinvest in aluminium production. Relatively cheap and stable electricity contracts were also offered to Norwegian companies, such as Elektrokjemisk, ÅSV and Hydro (Sogner 2003: 141-173). Similar governmental policies also influenced the decision of Sør-Al to build the aluminum plant at Husnes (1965). In this case, however, the foreign company AIAG/COMPADEC, owner of the proprietary technology, prohibited Norwegian companies and the Norwegian state from owning stock in the new company. AIAG thereby managed to retain control of their technology, knowledge about the aluminum market in house (Tjelmeland 1987: 24-39).

More than Norwegian institutions alone enabled Elektrokjemisk to enter into aluminium production. As already mentioned, US antitrust policy forced Alcoa to let other competitors like Reynolds and Kaiser enter the market. However, these new companies were not interested in supporting the Söderberg technology and the patent-pool that Elektrokjemisk had established as a technology supplier to the aluminum industry, and sought to develop their

own pre-bake smelting technology (Sogner 2003: 141-173). Even Alcoa wished to develop its own pre-bake technology, rather than rely on Elektrokjemisk's Söderberg technology. These developments limited further development of the Söderberg technology, and in the long run led to its replacement by other technologies. The Söderberg technology currently accounts for only 27% of global primary production, mainly at old plants in (2001). New plants and investments at old plants utilize prebake (IAI: 2006). Elektrokjemisk had no choice in its efforts to continue to exploit the Söderberg system, the financial backbone of the company (Sogner 2003: 141-173), other than entering production of aluminum. Elektrokjemisk's efforts to enter aluminum production relied heavily on the technological system that Alcoa could offer for upstream and downstream activities regarding innovation, production and sales. Elektrokjemisk built two aluminium plants, at *Mosjøen* (1958) and *Lista* (1971) in a joint venture with Alcoa (Sogner 2003: 190-195).

The third Norwegian actor, Norsk Hydro, had since the early 20th century sought to become an aluminium producer, but its lack of bauxite supply and access to technology precluded its entry (Johannesen et al 2005: 233-256). After 1945, however, the Norwegian government's industrial policies and the presence of new international actors seeking new markets facilitated Hydro's entry. When Harvey Aluminium entered the primary aluminium industry in the late 1950s, the company needed more smelting capacity, and the nation's inexpensive electricity supply as well as its proximity to the European market made production in Norway an attractive option. Its limited technological capabilities in aluminium, however, meant that Hydro could only provide the power supply, and had to team with foreign companies, just as had been the case in the early 20th century. In 1963, a joint venture of Hydro and Harvey Aluminium built a vertically integrated plant for aluminium smelting, rolling and extrusion. Norwegian financing was provided by Hydro and the Norwegian state (Johannesen et al 2005:

233-256). This facility enabled Hydro to build up new competences in many stages of the aluminium value chain. But in-house R&D on aluminium within Hydro was out of the question, since the firm did not have an experienced aluminium division. Hydro's insufficient knowledge and experience on the aluminium smelters became apparent in the mid-1970s, after Hydro purchased Harvey Aluminium's share of the joint venture and the plant began to experience production and efficiency problems (Johannesen et al 2005: 402-409). In 1977, the company established a R&D centre at Karmøy aluminium plant, consisting of a "metallurgical development group" with large scale laboratories and research groups focusing on extrusion, casting and rolling. Karmøy also began to collaborate more with other Hydro corporate operations which had an established R&D centre at Porsgrunn (Gjølme Andersen and Yttri 1997: 246-251).

Until the mid 1960s, Norwegian R&D investment was low within the aluminium industry itself and within the university/research institute sector.[10] Moreover, collaborative R&D between the aluminium companies and other organisations in the Norwegian innovation system was nearly absent due to the companies' focus on secrecy and their unwillingness to fund basic research. The production of aluminium in Norway until the mid 1960s has even been characterised as "pre-scientific" (Gulowsen 2000: 140-159). This characterization is certainly controversial and may be oversimplified, but it points to the fact that neither Norwegian R&D organisations nor universities had any substantial R&D or innovation collaboration with the aluminium producers. Things gradually changed during the 1950s and 1960s, as graduates from NTH were recruited into the industry and university-industry linkages were developed, partly due to personal networks. Furthermore, R&D investment in aluminium in Norway began to grow in the mid 1960s, when ÅSV started to collaborate more with NTH; the Centre for Industrial Research (SI); the Institute for Energy Technology (IFE);

and the Foundation for Scientific and Industrial Research (SINTEF) on plant automation and electrolysis processes, resulting in increased productivity (Wulff 1992, Gulowsen 2000).

A path of control (1986-)

The global aluminium industry's structure is less concentrated than it was in the early 20th century, and numerous actors have obtained access to technology and knowledge, raw materials and markets. In 2002, some 20 companies accounted for about 65% of the world's production, and most were aluminium specialists (IAI: 2002). Waves of acquisitions and mergers have been common in the aluminium industry since its inception in the late 1880s, and continued during the 1990s and early 21st century. During the 1990s, Alcoa took over Alumax (US independent producer) and Reynolds, while Canadian Alcan, French Pechiney and Swiss Alusuisse carried out a three way merger (Raw Material Group 2003). Recently (October 2006), one Russian company, Rusal, merged with its Russian rival Sual and the Frence Glencore firm, displacing Alcoa and Alcan to become the worlds' largest producer of primary aluminium with 4 million tonnes a year, and 11 million tonnes of alumina (Times 2006).

An important feature of innovation and production in the aluminium industry is vertical integration, which have always been a key organisational feature and a survival strategy for most aluminium companies. However, as for the Norwegian companies they did not fully integrate vertically until the mid 1980s. Companies that have not vertically integrated have been subject to takeovers (Wallace 1937, Peck 1961, and Stuckey 1983). There can be many motives and drivers behind vertical integration (both upstream and downstream) such as securing access to raw materials, improving access to markets, enabling horizontal expansion, or enabling innovation (Armour and Teece 1980, Teece 1996, Cassiman (ed.) 2006). Having

failed to pursue vertical integration strategies through much of the 20th century, Norwegian companies have begun to adopt this strategy in the last two decades. An unexpected interruption in supplies of alumina or power are very costly. Integration upstream enables primary producers to acquire increased leverage over the alumina supply, which is especially important during times of high demand for raw materials. Another strategy is to "lock in" independent alumina suppliers with long-term contracts. For example, Hydro Aluminium presently holds equity interests in three alumina refineries in Brazil, Jamaica and Germany, but the company also has long-term contracts with other bauxite-aluminium multinationals such as Comalco.

Although they have not always been vertically integrated, the Norwegian primary producers have all been part of larger conglomerates operating within other industries, in contrast to the American case of very large, vertically integrated specialist producers (Chandler 1962: 337-340). Until very recently, Hydro Aluminium consisted of a large oil and energy division, one aluminium division and one of "other businesses"[11]. In addition to its aluminium smelters, Elkem ASA has business operations in energy, silicon metal, foundry products, microsilica, carbon, calcium carbide and solar energy. In both Hydro Aluminium and Elkem Aluminium, aluminium production and innovation has been affected by this diversified structure. For example; much of Hydro Aluminium's recent expansion has been financed by Hydro's revenues from energy and oil (Lie 2005: 172-202). Innovation in Elkem Aluminium also has been heavily influenced by the cash flow among the different divisions.[12] In the late 1980s, Elkem produced relatively simple products and competed on volume. The collapse of the Soviet Union in 1989-1991 led to large exports of aluminium into Western Europe and USA, causing aluminium prices to fall dramatically. Elkem was nearly bankrupt in 1992, and needed to change its strategy in order to survive. One company director explained that they

had to consolidate and sell unprofitable business activities, and shifting the company's focus to becoming the best low-cost producer of aluminium. The success of this strategy by the late 1990s enabled Elkem to acquire the downstream company Sapa in 2003.[13] Hydro Aluminium AS was established in 1986 through the merger between Norsk Hydro and the Norwegian state-owned Årdal og Sunndal Verk (ÅSV) with the strong support of the Norwegian government. Hydro acquired the German Vereinigte Aluminiumwerke AG (VAW) in 2002, making Hydro Aluminium became the fifth largest producer of primary aluminium in the world (Roskill Information Services 2003).

Integration, acquisitions and mergers have been key survival strategies for primary producers of aluminium. In addition to increased market share, the companies gain access to new technology and access to new knowledge through R&D centres at the plants of former competitors and their networks in their innovation system, such as universities and research institutes. This may be one major benefit of integration.[14] For example, after Hydro's acquisition of VAW, the company obtained a dominant position in the German aluminium industry, and may benefit from their stronger linkages to the German innovation system. According to one company executive, "researchers and engineers in the former VAW system are working together with the Hydro-people" [15] Similarly, when Alcan and Pechiney merged in 2003, Alcoa acquired Pechiney's smelting technologies AP 18 and AP 30, seen as the best technologies available for license on the commercial market in terms of their cell amperage, efficiency of cells (measured in current efficiency) and number of cells (EEC: 2003). Analysts at the time suggested that Alcan would benefit from its improved ability to apply the Pechiney AP30 and the more modern AP50 cell technology, which is not available via licensing (Metal Center News: August 2003). According to Grinberg (2003: 98-99) and Alcan (2006: 9), the AP technology package now is the lowest-cost process technology in smelting.

Bauxite is still refined into aluminium oxide (alumina) and then electrolytically reduced into metallic aluminium, as one engineer said: “What we really are doing, is fine-tuning the processes that were invented over 100 years ago”.[16] Thus, the Hall-Héroult process is a mature technology, but R&D on productivity and environmental improvements remains active. Reducing energy requirements has always been a major driver for innovation[17], and the energy required for production has steadily been reduced. In 1899, smelters used over 50 kWh to make a kilogram of aluminium from alumina (IAI: 2006). The best smelters today require only 13kWh, while the Norwegian smelters use 13-14 kWh/kg, better than the world average (Grimsrud and Kvinge 2006).

Governments across the world are increasingly active regulators of aluminium companies’ operations because of environmental regulations, partly due to the Kyoto agreements on CO2 emissions, and much of the R&D in the Norwegian aluminium industry focuses on environmentally friendly process technologies. Norwegian smelters are among the leaders in environmentally friendly technologies (Hydro 2004b) and reduced their PFC emission (CO2, CF4, C2F6) by 62 percent during 1990-2005 while increasing production by 61 percent in the same period (Norsk Industri 2006). Reducing PFC emissions from primary production relies mainly on improved alumina feeding techniques through computer controls, trained operators, improved computer control to optimize cell performance, and monitoring cell operating parameters (U.S Environmental Agency). Hydro Aluminium even finds that its technological leadership in this field can be an advantage when acquiring plants and penetrating new markets, where national environmental legislations are of concern[18]. Norwegian smelters equipped with the old Söderberg technology face shutdowns because of the OSPAR convention (Protection of the Marine Environment of the North-East Atlantic) that guides

international protection of the marine environment of the North-East Atlantic. The plants at risk of shutdown are Karmøy, Årdal and Høyanger, all of which are run by Hydro. However, at some of these plants (e.g. Årdal), production nevertheless is expected to rise, because of increased cell amperage (Hydro 2003, 2007)[19]. Lista, owned by Elkem also has Söderberg production lines, but has managed to reduce their emissions significantly by improving the Söderberg technology (Teknisk Ukeblad: 2006).

Although the production costs determine the competitiveness of the smelters, these costs can be reduced by developing better cell technology. It has been claimed that Hydro has developed a cell system that it one of the "best in the world" (NTB: 2004). The latest investment in new smelters and related technology by Hydro at Sunndal (2003) was about 5.6 billion NOK, the largest investment in the Norwegian onshore industry in the last 20 years (Hydro 2004a). Prior to this overhaul, the smelter used HAL230 cells, considered by Alcan to be one of the second best technologies that are licensed (EEC 2003). Hydro Aluminium claims that the smelter now is one of the most efficient (and largest) in the world, with 350 new Prebake cells that use Hydro's proprietary technology, HAL250, with each cell having an amperage of 275 kA. The HAL250 technology will not be licensed to other firms, according to Hydro (EEC: 2003); only the "next-best" technology is licensed to other companies.

Norwegian producers' R&D activities take place in Norway and abroad. Company directors stress that the companies still have important R&D collaborations with the Norwegian University of Science and Technology (NTNU), and SINTEF. One company research director argued that NTNU has few academic equals in competence on aluminium. The recruitment of engineers by Norwegian aluminium companies has for a long time relied on students from NTNU, and the companies work closely with the University, even influencing the type of

education and research that is carried out.[20] Hydro Aluminium has R&D centres at its aluminium plants in Norway and around the world. R&D on electrolysis in Norway is mainly carried out at Sunndal and Årdal, while the company conducts R&D on alloys at Karmøy. Pure aluminium is rarely used by customers, and alloys therefore are important in meeting the need of clients in the manufacture of semi-finished goods (Le Roux: 2002: 727). Typically, customers (e.g. the automotive industry) require specific material properties, and manufactures of aluminium develop alloys to meet these performance requirements. Iron, silicon, zinc, copper and magnesium are among the materials combined with aluminium to produce metals with various properties for applications in semi-fabricated products and end-user products. These downstream fabrication activities are key drivers of developing new alloys. Thus, interaction along the value chain is important for innovation activities.

Corporate R&D investment by the diversified firm Hydro amounted to 716 mill NOK in 2005, of which 226 mil. was spent on energy and oil, and 456 mil. NOK on aluminium. About 50% of their R&D budget on aluminium is spent abroad (Hydro 2005b), most of it in Germany due to the acquisition of VAW in 2002.[21] Hydro Aluminium also has R&D collaborations with technical universities in Germany and in the US. Hydro has developed its own smelting technologies, but Elkem is more dependent on its American partner Alcoa. The Prebake technology that gradually has replaced the Söderberg technology was developed within Alcoa. However, most of the improvements on the Söderberg technology are done by Elkem, which has a research centre at Kristiansand that focuses on the Söderberg technology and carbon technology[22]. The Norwegian aluminium companies have enjoyed long-term support from the Government. Management at Norsk Hydro refers to “the Hydro Model”, in which the Norwegian state is one of the major owners of the company, supports its national champion, but plays a minimal role in management. Hydro has during its history from 1905

obtained economic privileges due to its Norwegian state ownership (Lie 2005), but the formerly strong ties between Hydro and the Government now are looser. For example, the liberalisation of electricity market, combined with low levels of investment in new capacity, have increase electricity prices and have made long-term electricity supplies harder to obtain. In periods of high demand and high aluminium prices, producers with relatively expensive energy can cope with this. When aluminium prices drop, however, high energy-cost plants may shut down. Hydro's German plant in Stade, Germany was closed in 2006 because it could not cope with the substantial increase in German power prices during the recent years. The increased difficulty of obtaining long-term power supplies, combined with the increased feasibility and attractiveness of investment in new capacity in developing countries where power is less expensive, mean that Norwegian smelters will have to be extremely energy efficient in order to survive.

What do these concerns imply for the future of the Norwegian aluminium industry? Analysts expect the global market for aluminium to double to over 60 million tonnes in 2020, reflecting overall growth in demand and in particular, surging markets in China, India and Russia (Alcoa: 2005). Companies are not likely to invest in new Norwegian capacity since power prices that are predicted to remain high and the fact that most of the Norwegian long-term power contracts expire in 2010. For example, at Sør-Al the repricing of power to current levels will increase the plant's annual production costs by nearly 40 million USD a year, which may force the smelter to shut down (Industriavisen: 2006). The president and chief executive officer of Hydro predicts that most aluminium plants in Europe will close during the next 10-15 years due to high energy prises and by global restructuring of the aluminium industry (E 24: 2005). Thus, the future prospects for the Norwegian primary aluminium industry appear to be grim, and current expectations concerning these future prospects are

already influencing innovation and production strategies. Hydro Aluminium is focusing future investments within its aluminium business on upstream activities, and will shut down costly primary plants and replace them by new competitive capacity in “energy-rich areas” outside of Norway (Hydro 2005b). Moreover, since we know that most R&D staff and their large scale laboratories need to be located close to the smelters, the researchers and engineers working within Hydro may have to relocate, exit, or focus on other aluminium-related R&D.

Conclusion

The case of the Norwegian aluminium industry adds important insights to the innovation system literature concerning the effects on a subnational “sectoral” innovation system of developments in both the national and the global innovation and production system. The competitiveness of Norway’s aluminium plants today, which is crucial to long-term industry survival, depends on a few fundamental factors, namely; improvements in the cost competitiveness of Norwegian smelters by improved energy efficiency, reductions in the capital costs per production tonne, environmental considerations, and improvements in the quality and functionality for specific applications of the metal.

The innovation and production system of the Norwegian primary aluminium industry has changed during the last 100 years. Worth mentioning here is the changing characteristics of the actors and networks, technologies and knowledge and the institutions during the three phases. In the first phase from 1908-1945, the locus of innovation resided first and foremost abroad. Production facilities were created and run by foreign companies that wanted to take advantage of the relatively cheap hydro power that was available in Norway‘s waterfalls. Other than the anode innovation of Elektrokjemisk, developed in collaboration with Alcoa, most of the technology and knowledge of Norway’s aluminium industry during this period

was developed in-house by these companies, which also exerted considerable market power through vertical integration and cartels. As explained by Wicken (2007), the Norwegian aluminium industry nonetheless represented a radical new path in the Norwegian NIS as it brought new capital, new technologies, new knowledge and new actors into the system.

In the second phase (1945-1986), the Norwegian aluminium industry gradually created a more autonomous path in innovation and production. The Norwegian Government created supporting institutions that in combination with domestic firms' strategies laid the foundations for entry into primary aluminium production by the national champions Hydro and Elektrokjemisk. Global networks and access to foreign technology remained essential – the joint ventures with Harvey, Alcan, Alcoa and European companies secured alumina supply, technology transfer, collaboration, and market access. US antitrust policy was crucial in weakening the Alcoa monopoly and enabling other US and non-US firms to enter, creating numerous new opportunities for international collaboration and technology access by Norwegian firms. Marshall Plan financing for ÅSV also facilitated the entry of a state-owned Norwegian national champion in the early 1950s, and illustrates the important influence exercised by global institutions on the industry's development within Norway. Beginning in the mid 1960s, Norwegian aluminium companies improved their knowledge base through increased in-house R&D activities and interaction and collaboration with other Norwegian organisations such as NTH, SINTEF and IFE.

The third phase (1986-) is first and foremost associated with the creation of Norwegian vertically integrated aluminium companies and horizontal expansion, typified by the merger of ÅSV and Norsk Hydro (1986). This merger also created a stronger aluminium company in terms of technology and knowledge and networks. Hydro was experienced with the

production and sales of semi-fabricated products, while ÅSV had developed their own electrolysis smelting technology, which Hydro further developed into one of the best available production technologies. The new company was able to strengthen its technological and market position, and avoided a takeover by larger multinationals. Elkem has continued their smelting technology collaboration with Alcoa and has expanded downstream through the acquisition of SAPA.

[TABLE 3 ABOUT HERE]

The Norwegian aluminium industry has been supported by a network of cooperative relations among industry firms, the Government, professional associations, and other organisations. In turn, this has supported investment in innovation and modern, environmentally friendly production capacity. Governmental policies, public and semi-private R&D and education programmes have supported the firms and during post war period in particular have reinforced the industry's position in the Norwegian innovation system. Moreover, the influence of domestic policies, on the domestic industry's evolution has been enhanced by powerful global sectoral forces at play represented by foreign states and large multinationals. Indeed, the ability of Norway's postwar "industrial policy" in this sector to operate in concert with, rather in opposition to, larger global trends within the industry is noteworthy.

Castellacci (2007) has pointed out that sectors need support from the NSI in order to become industrial leaders. This certainly goes for the Norwegian aluminium industry as well as the Norwegian oil industry (See Engen 2007). In addition, however, this study shows that innovation and production in the aluminium industry depend as well on global flows of technologies and knowledge, global networks, and global institutions. The innovation system

of the Norwegian aluminium industry is shaped by national and global forces, which means that an international perspective on the innovation and production systems is essential to understanding the sector's historical evolution and prospects.

Notes

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[2] It has also been claimed that Norwegian firms in the process type sectors such as aluminium are subject to a 'systemic lock-in' in their NIS (Narula 2002). The sources of innovation come mainly from the national innovation system, consisting of strong and supporting Norwegian organisations and institutions, but the overall economy remains committed (and, arguably, overcommitted) to relatively mature, long-established industrial sectors.

[3] "A sector is composed of heterogenous agents that are organisations or individuals (e.g. consumers, entrepreneurs, scientists). Organisations may be firms (e.g. user, producers, and input suppliers) or non-firms (e.g. universities, financial institutions, government agencies, trade-unions, or technical associations), and include subunits or larger organisations (e.g. R&D or production departments) and groups of organisations (e.g. industry associations)." (Malerba 2005: 385)

[4] Vigeland Metal Refinedy (Vennesla plant) is not included in this analysis, since the plant produces a somewhat different product – superpure aluminium (99,99%). Today it produces about 6500 tonnes of super-pure aluminium. The plant imports its primary metal from Russia, and is owned by Norsk Hydro (50%) and Alcoa (50%).

[5] Interview with plant manager December 2005 at Mosjøen, and interview with company director at Elkem September 2005, Oslo

[6] Compagnie de Produits et Electrométallurgiques was founded in 1855 and produced aluminium through chemical processes for about 30 years, applying the Deville-process that was developed in 1860. This company became known as Pechiney after the merger with SMEF, and until 1886 was the dominant aluminium company in France. But the new electrolysis process made the Deville technology uncompetitive.

[7] As a part of Alcoa, the Canadian operation was incorporated in 1902 as Northern Aluminum Company, but in 1925 its name was changed to Aluminum Company of Canada, Limited. In 1928, a federal antitrust suit forced Alcoa to divest its principal subsidiaries outside the United States, including Aluminum Company of Canada, Limited, which was reorganized as an independent Canadian company that focused on the development of the industry in Canada and internationally. The directors and management were independent of Alcoa from 1928

onwards; a final adjudication of legal proceedings in 1950 forced the divestiture of overlapping equity ownership between the two firms (AluNET International: 1999)

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[8] "…industries in which being ahead of one's competitors in product or process technology, or in production and marketing, gives firms an advantage in the world markets" (Mowery and Nelson 1999: 2).

[9] After the 2nd World War the plant (Venesla) was reconstructed to produce super-pure aluminium.

[10] With the exception of the R&D investments and collaboration that produced the Söderberg system and the Pedersen process for extracting alumina out of Norwegian clay, there had been little R&D and little collaboration among metals-processing companies and other actors within the Norwegian NSI (see Wulff 1992)

[11] In 2007 Hydro merged with the Norwegian oil company Statoil producing a firm named Hydroil.

[12] Interview with a company director at Elkem, September 2005

[13] Interview with a company director at Elkem, September 2005

[14] Based on interviews with company directors in Elkem, September 2005, and Hydro Aluminium, October 2006

[15] Interview with a research director at Norsk Hydro, January 2006, Oslo

[16] Interview with plant engineer at Elkem Mosjøen, December 2005, Oslo

[17] Interview with a research director at Norsk Hydro, January 2006, Oslo

[18] Interview with a research director at Hydro Aluminium, Primary Metal, October 2006, Oslo

[19] Interview with Thomas Knutzen at Hydro, press contact for Hydro Aluminium, 13 April 2007

[20] Interview with a research director at Norsk Hydro, January 2006, Oslo

[21] Based on Hydro annual report 2005, and interview with a research director at Norsk Hydro January 2006, Oslo

[22] Interview with company director at Elkem, September 2005, Oslo

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Aluminium glossary

Source: Aluminium Glossary: http://www.metallurgaluminium.com/glossarymain.html

Alloy: A mixture containing more than one element.

Anode: Positive electrode made of carbon in electrolytic cells used in the smelting process.

Bauxite: A soil type and ore derived from the weathering of granite (sialic parent rock), and depleted of nearly all soluble elements. Aluminium oxides are virtually all that remain after calcium, potassium, sodium and silicon have been leached out. Bauxite is the principle ore of aluminium, and is predominantly found in tropical and sub-tropical regions.

Cathode: Negative electrode in electrolytic cells used in the smelting process.

Casting: Pouring molten metal into moulds at any stage of the fabrication and manufacturing process.

Cells (or “pots”): A reduction cell in which aluminium is produced

Cryolite: Salts-based flux (e.g. potassium aluminium fluoride).

Extruding: The act of deforming solid aluminium, usually in the form of a cylindrical billet, by pushing it from an enclosed container through a die to form a product of consistent cross section.

Ingot: Metal cast in a shape that is convenient for handling, storage, shipping and remelting. Ingots may be small enough to be stacked and handled by one person, or in the case of a larger T-ingot, may be designed to be handled by a forklift.

Process control: The act of controlling the key parameters of a process to try to ensure product consistency.

Smelting: Process of producing molten aluminium by the reduction of alumina.

List of Abbreviations

AIAG: Aluminium Industrie Aktien-Gesellschaft

Alcoa: Aluminum Company of America

Alcan: Aluminum Limited of Canada

DNN: Det Norske Nitridaktieselekap

ECA: Economic Cooperation Administration

Froges: Société Electrometallurgique Francaise

IAI: International Aluminium Institute

LME: London Metal Exchange

NIS: National Innovation System

NTH: Norwegian School of Science and Technology

NTNU: Norwegian University of Science and Technology

NTNF: Research Council for Scientific and Industrial Research

OECD: Organisation for Economic Co-operation and Development

Pechiney: Compagnie des Produits chimiques d'Alais & de la Camarque

PIL: Federation of Norwegian Process Industries

RCN: The Norwegian Research Council

SITC: The Standard International Trade Classification

SEMF: Societe Electrometallurgique Francaise

SGN: Sociéte Generale des Nitrures

SINTEF: The Foundation for Scientific and Industrial Research

SI: Senter for Industrial Research

SIS: Sectoral Innovation System

TBL: The Federation of Manufacturing Industries

VAW: Vereinigte Aluminiumwerke AG

ÅSV: Årdal og Sunndal Verk

Figure 1: The Norwegian aluminium industry, production 1990-2005, Source: PIL 2005.

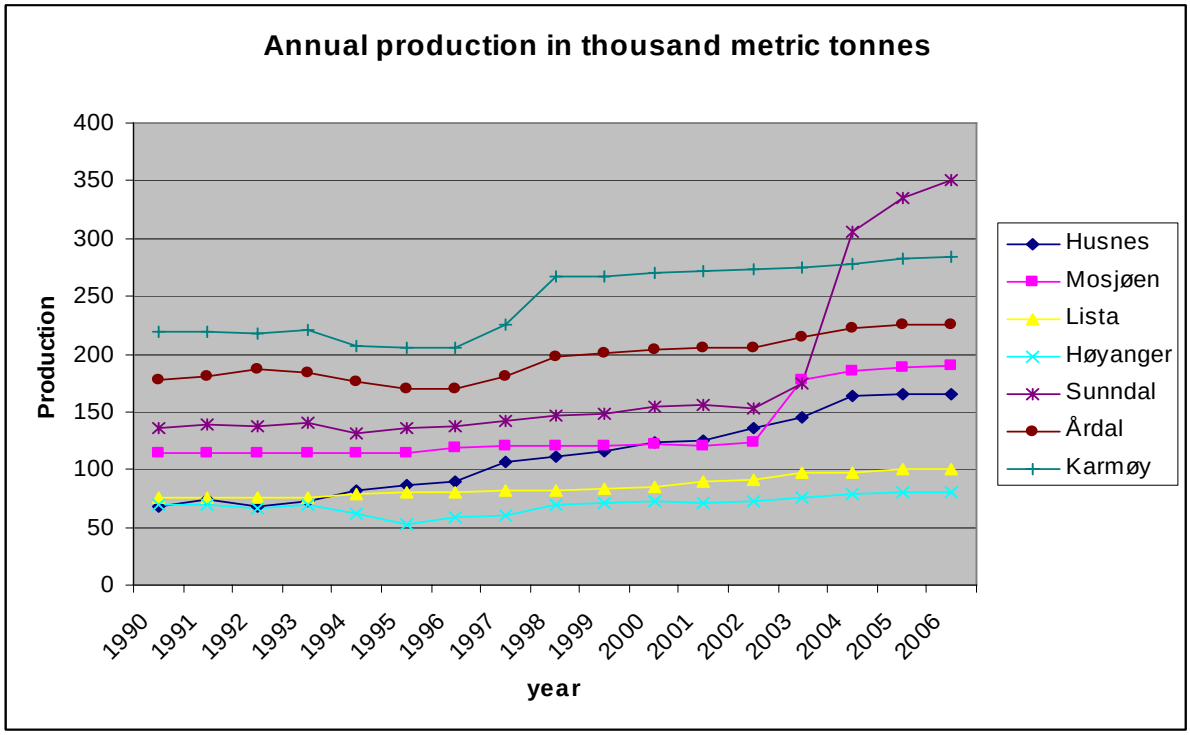

Table 1: World average smelter cost structure in and Hydro Aluminium's smelter costs structure in 2005 (%)

	World Average	Hydro	Markets influencing the smelter production cost at Norwegian smelters
Alumina	40	33	World market
Carbon	10	9	World market
Power	26	28	Regional and national markets
Casthouse	4	7	Local markets
Labour	7	10	Local markets
Other	13	13	Local markets

Sources: Hydro 2005a / CRU 2005 / Grimsrud and Kvinge 2006.

Table 2: Companies operating at primary aluminium plants in Norway during the three phases.

Plant locations	Operating companies and their ownership*	Production start - plant closure
Stongfjorden	*Stangefjordens Elektrokjemiske fabrikker* 1906-1945: British Aluminium Company (BACO)	1908 – 1945
Vigelands Brug	*AS Vigeland Brug* 1908-1912: Anglo –Norwegian Aluminium Company 1912-1945: BACO	1908 - 1945 [23]
Eydehavn	*Det Norske Nitridaktieselskap (DNN)* 1912-1913: Elektrokjemisk A/S + SGN 1913-1918: SGN + Pechiney 1923-1958: Pechiney + Alcan + BACO 1958-1976: Alcan + BACO	1914 – 1975
Tyssedal	*Det Norske Nitridaktieselskap (DNN)* 1912-1923: Pechiney 1923-1958: Pechiney + Alcan + BACO 1958-1976: Alcan + BACO 1976-1981: The Norwegian State	1916 – 1981
Høyanger	*A/S Høyangfallene Norsk Aluminium Co:* 1915-1923: Norsk Aluminium Co (NACO) 1923-1967: Alcoa/NACO** *Årdal og Sunndal Verk (ÅSV)* 1967-1986: The Norwegian State *Hydro Aluminium Høyanger* 1986- Hydro Aluminium	1917 – still active
Glomfjord	*Haugvik smelte verk* 1926-1931: International Aluminium Company 1931-1940: Allicance Aluminium Clie (cartel: Pechiney, Ugine, BACO, Alcan, AIAG, VAW, Aluminiumwerke Bitterfeld.	1927 -1942
Årdal	*A/S Årdal Verk* 1946-1951: the Norwegian state *Årdal og Sunndal Verk (ÅSV)* 1951-1966: the Norwegian state 1966-1979: Alcan + the Norwegian State 1979-1986: the Norwegian State *Hydro Aluminium Årdal* 1986- Hydro Aluminium	1948 – still active
Sunndal	*Årdal og Sunndal Verk (ÅSV)* 1951-1966: the Norwegian State 1966-1979: Alcan + the Norwegian State 1979-1986: the Norwegian State *Hydro Aluminium Sunndal* 1986- Norsk Hydro***	1954 – still active
Mosjøen	*Mosal/Elkem Aluminium Mosjøen* 1957-1963: Elkem + AIAG 1963 -Elkem + Alcoa	1958 – still active
Husnes	*Sør-Norge Aluminium (Sør-Al)* 1962-1976: AIAG/Compadec (later Alusuisse) + Den Norske Creditbank (DnC) 1976-2000 Hydo + Alusuisse 2000- Hydro Aluminium + Alcan	1966 – still active
Karmøy	*Alnor/Hydro al* 1963-1973: Harvey + Hydro 1973- Hydro Aluminium	1967 – still active
Lista	*Elkem Aluminium Lista* 1962- Alcoa + Elkem	1971 – still active

Source: Author's construction based upon Tresselt 1968, Innvik and Kamsvåg 1996, Rinde 1996, Sogner 2003, Lie et al 2005, Fasting 1965, Kollenborg 1962, Tjelmeland 1987.
***** During Second World War Germany took control over the industry and founded Nordische Aluminiumgesellschaft, in 1941 two companies – Nordisk Lettmetall and Nordag were supposed to run the existing plants, and build new projects: the "Koppenberg Plan", however, although new projects where initiated, larger capacity was not achieved during the war.
****** In 1928 Alcoa divested itself from its subsidiaries outside the US, including the Aluminium Company of Canada (Alcan), and transferred these companies into a single company that organised foreign plants.
***Hydro Oil merged with Statoil in 2007, divesting itself from Hydro Aluminium

Table 3: A stylised overview of the key building blocks in the innovation and production system of Norwegian primary aluminium from 1908-2007.

	Technologies and knowledge	**Key actors and networks**	**Institutions**
1908-1945: global sectoral sources dominate	-The Söderberg anode (world dominance until the 1950s). -The wider smelting technological system is developed and controlled through technological monopolies by MNE's	-Elektrokjemsk (technology supplier). -Innovation collaboration between Elektrokjemisk and Alcoa. -Alcoa/Alcan, AIAG, Pechiney and BACO initiate the Norwegian projects	-Monopolies (US) and oligopolies (Europe) -Cartels controlled by MNE's on production at the various sites and the sales of aluminium and bauxite worldwide.
1945-1986: Creating a path of autonomy	-ÅSV develops its own cell technology. -Harvey Aluminium provides Hydro with technology. -The large MNE's loose their technological monopoly. -Automatisation of the technological system at the plants	-Nationalisation of the industry: Hydro, Elkem and SørAl. -The Norwegian State. - Joint ventures between Norwegian firms and the foreign industrial leaders. -Norwegian R&D at production sites. -R&D linkages to the between domestic firms and at NTH, SINTEF, SI and IFE.	-The Monopoly in the US broken. -There where oligopolies in the US and in Europe. -Norwegian firms gained national support -The Marshall Plan + ECA.
1986- A path of control	- Norwegian R&D groups and divisions abroad. -Global orientation and control with regard to technology development, knowledge base, and production. -Increased focus on environmental technologies	- Norwegian companies expand and integrate vertically. Stronger linkages to foreign universities and R&D organisations	-Liberalisation and less national support with regard to tax incentives, electricity agreements. -Higher standards regarding environmental control nationally and Globally (Kyoto and OSPAR).