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Slow technologies and government intervention: Energy efficiency in industrial process technologies

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Abstract

Many government interventions seek to increase the efficiency of industrial processes and to stimulate innovation. In this article we present and analyse four case studies of innovations in energy-efficient industrial process technologies: two in the paper and pulp industry and two in the iron and steel industry. We study the various networks around these technologies and investigate how they are affected by government intervention. An important relationship (an inverted U) is found between the momentum of the networks and the effectiveness of government R&D support for energy-efficient process technologies. It is concluded that R&D support can only be effective when it takes account of the characteristics of so-called 'slow technologies'.

Keywords: Energy efficiency; Industrial process technology; Innovation; R&D support; Momentum

1. Introduction

In the last few decades, energy efficiency in industrial process industries has interested governments, and increasingly they have been willing to invest in it. Improving energy efficiency is seen as an important option for mitigating human-induced climate change (IPCC, 2001; UN, 1997). Whereas spending on government energy R&D support has generally fallen off, government R&D support for end-use energy efficiency has been consistently increasing (WEA, 2000). In industrialized countries industrial energy-efficiency R&D support appears to be receiving preference over other end-use sectors such as buildings or transport (IEA, 1997; Dooley et al., 1998; Luiten and Blok, 1999). Fig. 1 gives an assessment of the R&D budget development in industrial energy efficiency in comparison to the general budget development in government energy R&D support.

This interest in industrial energy efficiency and these investments raise questions about the results of these investments. Does increased spending on R&D support lead to a more energy-efficient manufacturing industry? Does it accelerate the development of energy-efficient industrial process technologies? What is the relation between R&D support and the R&D investments of the industry itself? In short, what are the effects of this type of government intervention? Answers to such questions cannot be straightforward as it is notoriously difficult to assess the results of R&D. For instance, the selection of indicators of what R&D investments have accomplished is complicated and it is difficult to assess what would have happened without government R&D support (Sagar, 2000; Dooley, 2000; PCAST, 1997; Laestadius, 1998).

Our starting point in this article is that the effect of government intervention will depend on the dynamics of the manufacturing industry. What is needed, therefore, is an understanding of the characteristics and patterns of innovation in industrial process technologies (Nelson and Winter, 1977; Jacobsson and Johnson, 2000). We need, for instance, insight into the motivation of actors to be involved in the development of innovative industrial energy-efficient technologies. What are the dominant arguments to initiate, pursue or stop such activities? And how does governmental R&D support affect these decisions. How susceptible are firms to attempts to stimulate

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innovative developments? What are the relevant factors and dynamics at stake?

The dynamics of technological development in industrial process industries is somewhat unexplored. Several studies show that technological innovations that affect the core of the manufacturing process are relatively slow, i.e. they may take decades instead of years (OECD, 1996; Utterback, 1994; Knot et al., 2001). On the basis of these and our own studies we may define 'slow technologies' by the following interconnected characteristics:

- The sunk capital investment of the conventional production processes in the manufacturing industry heavily constrain new R&D activities.
- The different firms use the same type of production processes, which reduces the variety in technological development.
- The cycles for developing new process technologies are long (20–40 years) since the number of competing innovative technologies is limited, and existing technologies can be improved incrementally.
- Innovative technologies may be known for a number of decades but remain unexploited. They have to be recognized as a next-step-to-take in improving the performance of the existing production process.
- Manufacturing firms are only interested when an innovative technology is 'proven', and, if so, they will be implemented in existing facilities first. It can take considerable time before a technology becomes a proven option for the entire range of products manufacturing in a specific industry. A continuous up-scaling, most often two or three steps easily taking about 10–20 years, is required for convincing manufacturing firms.

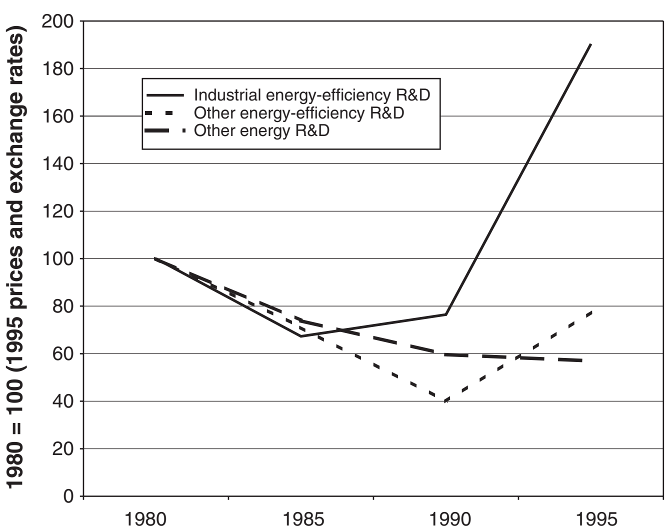

Fig. 1. Energy R&D expenditure trends 1980 and 1995 for 11 industrialized countries (IEA, 1997).

In this article we present four case studies of innovative industrial process technologies: two in the paper and pulp industry and two in the iron and steel industry. We have several arguments for this selection (see Table 1). First, both sectors are energy intensive: the worldwide manufacturing industry is the largest energy-consuming economic sector. Industrial emissions account for over 40% of carbon dioxide emissions of energy-end use. The energy consumption in the iron and steel industry, the chemical industries, petroleum refining, paper and paper and the cement industry are responsible for 45% of the total industrial energy consumption (IPCC, 2001) Moreover, the production of such basic materials is expected to remain a major energy-consuming activity in the future (WEC, 1995). Second, the four selected technologies are frequently mentioned in review studies on innovative energy-efficient technologies (Arthur, 1998; De Beer, 1998; Martin et al., 2000; IPCC, 2001). They are recognized as breakthrough technologies in energy efficiency, since they affect the core of the conventional production process and promise

Table 1
Overview of the case studies selected

Case study	Sector	Relation to production process	Energy efficiency	Present status
Shoe press technology	Pulp and paper	Replaces part of the wet pressing section of a paper machine	Mechanical water removal, less evaporation needed	Widely implemented
Impulse technology	Pulp and paper	Replaces part of the wet pressing section of a paper machine	Mechanical water removal, less evaporation needed	Status is uncertain
Strip casting technology	Iron and steel	Further integration of casting and rolling of liquid steel. Making hot strip mill superfluous	Reheating of cast steel is no longer needed	Claimed ready for commercial application
Smelting reduction technology	Iron and steel	Replaces conventional blast furnaces and coke ovens in iron making	More energy-efficient iron reduction process	Claimed ready for commercial application

Table 2
Classifying energy-intensive manufacturing industry in Pavitt's innovation taxonomy

Innovation-type firm	Industrial manufacturing sectors [ISIC Rev.3][a]	Energy-intensive	R&D intensity[b]	Indirect R&D intensity[c]
Supplier-dominated	Textiles, fur and leather [17–19]		0.23	0.55
	Pulp and paper [21 + 22]	X	0.31	0.57
Specialised suppliers	• Machinery [29]		1.74	1.84
Scale intensive	• Mining [10–14]		—[d]	—
	• Food and beverages [15 + 16]	X	0.34	0.39
	• Basic chemical industry [241]	X	—	—
	• Iron and steel [271 + 2731]	X	0.64	0.46
	• Non-ferrous metals [272 + 2732]	X	0.93	0.64
	• Non-metallic mineral products [26]		0.93	0.51
	• Fabricated metal products [28]		0.63	0.72
	• Motor vehicles [34]		3.41	1.03
	• Other transport Eq. [35][e]		1.58	1.45
	• Utilities [40–41]		—	—
Science based	Mineral oil industry (PR) [23]	X	0.96	0.37
	Chemicals and chemical products:			
	Excl. basic chem. [24]		3.2	0.64
	Incl. pharm. [2423]		10.47	0.88
	• Electro-technical industry:			
	• Office & comp. Eq. [30]		11.46	2.91
	• Electrical mach. [31]		2.81	1.15
	• Radio, TV & comm. Eq. [32]		8.03	1.37
	• Scientific instruments [33]		5.10	1.45

[a]Classification based on Pavitt (1984), CBS (1998).
[b]R&D intensity is the R&D expenditure divided over the production value of the industrial sector. Weighed average for ten countries (GDP purchasing power parities) Hatzichronoglou (1997).
[c]An input–output analysis leads to an R&D intensity that includes indirect R&D. The R&D investment of a supplying industry divided over the total products or goods. Via input–output analysis this R&D is attributed to the sectors who buy certain products or goods from this supplying industry. The indirect R&D is thus the R&D that is supplied in intermediate products or goods Hatzichronoglou (1997).
[d]R&D intensities not available Hatzichronoglou (1997).
[e]Excludes aerospace and shipbuilding Hatzichronoglou (1997).

substantial energy efficiency improvements. Finally, in all four technologies R&D activities occur and various attempts of government intervention have taken place (see Table 2).

2. Method

In the four selected industrial process technologies we are interested in when and how governmental R&D support can be effective. The focus in the case studies is on the networks of researchers, boards of directors, engineers and other actors. We studied how networks around energy-efficient technologies in these sectors evolved and investigated how they were affected by government intervention.

A basic idea of a network approach to innovation is that not all actors have an equally close relationship (Hakansson, 1987; Callon et al., 1992; Gerstlberger, 2004). In our case studies we decided to distinguish between a micro-level of activities—the micro-networks—and a meso-level, the so-called technology network. A micro-network is defined as a group of actors who co-operate in developing a specific industrial energy-efficient technology. They co-operate on the basis of specific skills and financial resources, they perform R&D activities, test materials and build prototypes. The actors in the micro-networks learn from their own R&D results, but they commonly also look at efforts within other micro-networks. The innovative technology, or a specific version of the innovative technology, materializes within the micro-networks. Micro-networks may be located within firms but will often extend beyond the boundaries of firms.

A technology network, on the other hand, is defined as the total collection of micro-networks around an innovative technology. They include the collaborations and joint efforts of researchers and firms, the conferences and specialized journals. As within micro-networks, learning occurs and appears as an important binding force. Of course, the activities in the micro- and technology networks do not occur in isolation. The actors will be embedded in a context, an "innovation background", which influences the R&D directions and perceptions of what is to be considered as an interesting direction for progress. The innovation background guides the various R&D agendas (Van Lente, 2000). Elements of the innovation background are the market in which the firms operate, existing business relationships, innovation patterns within and between industrial sectors, sectoral developments, and the conventional production technologies for manufacturing steel or paper (Lundvall, 1995; Edquist, 1997; Tsoutsos and Stamboulis, 2005). Fig. 2 shows the framework of micro-networks, the technology network and the innovation background.

The contribution of government R&D support to the innovative activities can be assessed and compared with the role of other incentives and decisions (Kemp, 1997). In our assessment of the effect of R&D support we make a distinction between: (i) Additionality: did financial R&D support lead to R&D that would not have happened without R&D support? (ii) Acceleration: did R&D support lead to an acceleration in technological development? (iii) Effectiveness: did the innovative technology eventually reduce the energy consumption?

In this study, we used two main sources of data: written material and interviews with experts. All kinds of written material were used: scientific articles, technical articles, articles from trade journals, conference proceedings, technical reports, patents, statistics and press releases. In addition, information was gathered in interviews. Consultation of experts is essential because the data and information in the dynamics of the sector are often not available in written (public) material. We conducted personal interviews, had elaborate telephone conversations, and used e-mail exchanges. The interviews were semi-structured and, in a second round, the expert interviewees were asked to comment on the interview text. In order to increase the reliability and to circumvent well-known pitfalls (Yin, 1989) such as selective and faded memories, vested interests and secrecy, information and statements were tested against statements made by other experts and against written sources. We consulted a large number of experts for each case study and tried to include representatives of all actors that were involved in the development of the specific industrial process technology.

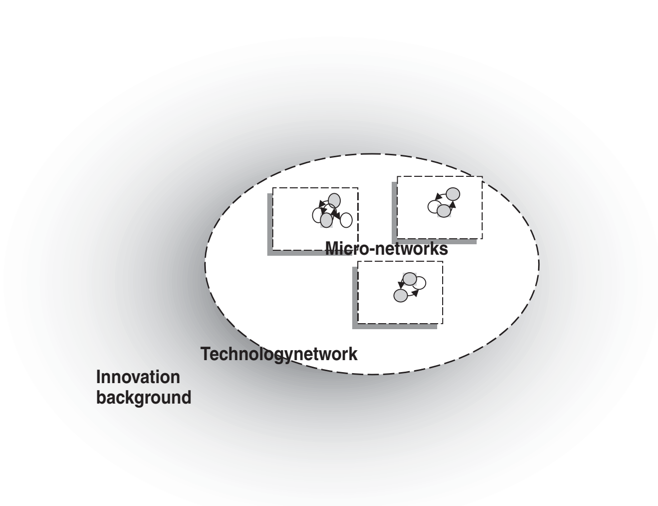

Fig. 2. The network-oriented framework used for analysing the development of industrial energy-efficient process technologies.

In case study methodology, both written and interview materials have to be carefully processed for two reasons (Yin, 1989). First of all, sources have intrinsic limitations, since experts interviewees and authors give their interpretation of why and how things happened. Not all data covered in articles are neutral or value-free facts. Secondly, the researcher interprets and structures the information from written sources and the accounts of the interviewees. Data collection in qualitative research means reconstructing and gaining understanding at the same time. Thus, data collection and data analysis overlap, and, therefore, it is important to organize data collection carefully. We adopted the following procedure:

- We contacted most of the experts more than once. The first round provided basic information about other actors, networks, agendas and artefacts. It also delivered suggestions for articles and the names of other experts we could contact.
- Written material was collected to map the first outline of the R&D trajectories, the micro-networks and the technology network.
- For each of the micro-networks, a description was made of the events and decisions that had taken place within that micro-network. These descriptions were used in a second round of interviews with the experts.
- The material gathered for the various micro-networks was also grouped under separate topical headings so that the various micro-networks could be compared and cross-linkages could be made. These descriptions were also used in a second round of interviews with the experts.
- The second round of interviews took place after a preliminary synthesis and analysis of the written material and the information and statements gathered in interviews. This second round was important for acquiring a proper understanding of the special peculiarities of the specific case.
- A draft version of each case study was sent to the industrial experts in order to solicit feedback, comments and suggestions (Tables 3 and 4).

3. Results: four case studies[1]

3.1. Shoe press technology

Shoe press technology is a papermaking technology that improves dewatering of the board or paper sheet in the wet pressing section and, therefore, reduces the need for evaporating drying. The improvement in dewatering is achieved through extending the residence time in the press. Developing this technology took about 13 years

[1]For a full account of the case studies see Luiten and Blok (2003a, b, 2004).

Table 3
Experts interviewed for each case study

Case study	# Micro-networks [active in 2000]	# Of specialists consulted [more than once]	# Of specialists that reviewed draft text case study
Shoe press technology (paper)	1 [2]	13 [7]	9
Impulse technology (paper)	2 [1]	26 [13]	14
Strip casting technology (iron and steel)	11 [6]	13 [5]	6
Smelting reduction technology (iron and steel)	9 [6]	20 [7]	14

(1967–1980). The technology network was small and consisted of only one micro-network, and for a long time only one firm. Although the idea for extending pressing time was acknowledged by others, only the people at the US machine supplier Beloit continued to believe that such a major new press design could be engineered. The shoe press implied a major change to the conventional roll press from an engineering point of view; a flexible belt had to be used instead of a steelen roll press. In spite of the various setbacks and the difficulties in achieving an engineering solution, the R&D activities were continued with huge dedication and belief. During those days, other major machine suppliers only slightly touched upon the idea but did not continue R&D. When Beloit had implemented a shoe press in their pilot paper machine, a board manufacturer and a fabric supplier—both well-known business partners to Beloit—became involved in the micro-network. The fabric supplier was involved to come up with a feasible belt at the moment that the first commercial shoe press for a board machine was already decided upon. They succeeded in time. Without the belt, the commercial introduction (1980) would have been delayed. Only by then, the technology network expanded and three other major machine suppliers also started R&D activities. They all developed improved shoe press designs with a 'closed' belt. Their designs were introduced in 1984, 1986 and 1990. The closed shoe press design showed a better performance at higher machines speeds. This is important because since papermaking has become a continuous operation, machine speeds have increased—and they will continue to do so into the future.

The major argument for developing shoe press technology was to increase the machine capacity of existing board machines and to reduce the capital intensity of new board machines. During the early 1980s, machine suppliers claimed advantages for other paper grades too. Only when conventional wet presses limited a further increase of machine speeds the shoe press became a proven technology in paper machines too, from 1994 onwards. Beloit succeeded in bringing this innovative technology to the market because of a continued belief that the press could be engineered in the end and that improving dryness at the exit of the wet pressing section was a key in making paper machines run in a more profitable way. In addition, Beloit had a 'proven' reputation as one of the worldwide major machine suppliers. Further R&D activities were stimulated by the market success of shoe press technology.

3.2. *Impulse technology*

Impulse technology is a papermaking technology that also increases dewatering of the board or paper sheet in the wet pressing section and, therefore, reduces the need for evaporating drying. It is claimed that forced steam formation in the paper sheet pushes water out of the sheet. Douglas Wahren, who invented this technology in 1970, anchored impulse R&D activities at the US National Pulp and Paper Research Institute 10 years after his first idea of impulse technology. Wahren contacted people at Beloit, the US machine supplier that had recently introduced the innovative shoe press. At Beloit, impulse technology was seen as a logical next step after the shoe press. A first micro-network emerged when both Beloit and the Canadian National Pulp and Paper Research Institute initiated R&D activities. Both claimed an increased energy efficiency and succeeded in obtaining government R&D support. Within the North-American micro-network four attempts to commercialize the technology failed (1989, 1993, 1994 and 1999) and Beloit's interest in the technology was gradually lost. Researchers at Beloit managed to continue R&D, but with a lower priority. Eventually, the North-American micro-network came to an end when Beloit's mother firm filed for bankruptcy in 1999. A second micro-network emerged in Sweden from 1990 onwards. The Swedish government offered the national pulp and paper research institute financial R&D support in order to start the development of this energy-efficient technology. After 6–7 years of planning, talking and negotiating, a major R&D programme was started. Today, only the Swedish micro-network is still active.

The major argument for developing impulse technology was to increase machine capacity in existing paper and board machines and to reduce capital intensity in new paper and board machines. Wahren's original claim about dewatering gains lost strength over time. The arguments for investing in impulse technology changed: the improvements in paper properties were increasingly stressed. Yet, many actors—machine suppliers, paper manufacturers and national pulp and paper research institutes—lost their

Table 4
Key patents and publications for each case study

Case study	Key patents and references
Shoe press technology	A large number of patents were issued (50–100), also after 1980. Some patents of Beloit: • Mohr WC, Francik CJ. US patent 3,804,707. Beloit. US, 1974 • Busker LH, Mohr W, Daane R. Figure eight cylinder press for defining an extended nip press. US patent 3,808,096. Beloit. US, 1974 • Hoff DI. Multiple belt press. US patent 3,797,384. Beloit. US, 1974 • Justus EJ, Hydrodynamically loaded web press with slipper bearing. US patent 3,783,097/reissued as RE 30,268. Beloit. US, 1974 • Mohr WC, Busker LH, Francik CJ, Bergström JI. Extended nip press. US patent 4,201,624. Beloit. US, 1980 Key articles written by Beloit employees: • Busker LH. Effects of extended nips on wet pressing. TAPPI 1971;54(3):373–378. • Justus EJ, Cronin D. Development of the extended nip press. TAPPI 1981;64(12):35–38.
Impulse technology	A large number of patents was issued (50–75) and many (scientific) articles and reports from various firms and research institutes. Key patents: • Wahren, D (1982) 'Methods and apparatus for the rapid consolidation of moist porous webs' US patent number 4324613, KMW, issued 13 April 1982 • Wahren, D (1978) 'Förfarande och anordning för konsolidering och torkning av en fukting porös bana' Swedish patent application 7803672-0, KMW Some key-references: • Arenander, S and Wahren, D (1983) 'Impulse drying adds new dimension to water removal' TAPPI Journal 66 (9) 123–126 • Larsson, H and Stenström, S (1998) 'Critical pressure control of delamination in impulse drying' TAPPI Journal 81 (7) 117–122 • Orloff, D I and Crouse, J W (1999) 'Impulse drying: status of the pilot-scale research program' TAPPI Journal 82 (9) 143–149 • Orloff, D I (1998) 'Impulse drying of board grades: An emerging technology' PaperAge 114 (12) 22–23
Strip casting technology	Bessemer applied for a patent in 1857. Steel-makers own key-patents. A number of articles give an overview of the historic development • Birat, J.P. (1999). Innovation in steel continuous casting: past, present and future. La Revue de la Metallurgie-CIT. 96 (11) 1389–1399. • Birat, J.P. (1992). Direct casting of thin strip. Endeavour. 16 (3) 110–116. • Cramb, A.W. (1989). New steel casting processes for thin slabs and strip. A historical perspective. Transactions of the Iron and Steel Society. 10 61–76. • Kubel, E.J. (1988). Direct thin strip casting. Metal Progress. (9) 55–62. • Tony, W.A. (1990). Near-net-shape casting no longer considered and advanced technology. Iron & Steelmaker. January 1990, pp. 22–26.
Smelting reduction technology	The basic principle goes back to the 1950s. Articles and patents were a first source of exchanging knowledge among micro-networks. A number of articles give an overview of the historic development. • Astier, J. (1991), Evolution or revolution to produce steel: direct reduction versus smelting reduction, in: La Revue de la Metallurgie—CIT, May 1991, pp. 443–451. • Birat, J.P. (1992), Direct casting of thin strip, in: Endeavour, vol. 16, no. 3, pp. 110–116. • Feinman, J. (1999), Direct reduction and smelting processes, in: Iron and Steel Engineer, June 1999, pp. 75–77. • Millbank, P. (1995), Direct route to iron gathers momentum, in: Metal Bulletin Monthly Technology Supplement, April 1995, pp. 21, 24–25. • Smith, R.B., M.J. Corbett (1987), Coal-based ironmaking, in: Ironmaking and Steelmaking, vol. 14, no. 2, pp. 49–75.

confidence in the performance and feasibility of impulse technology. More than 25 years of R&D activities and 15 years of government R&D support have not yet resulted in a proven technology. In addition, energy-efficiency improvements are uncertain. In spite of this, government R&D support was continued and accelerated the development of impulse technology and researchers continued to attract government R&D support by claiming an improved energy efficiency, but their major interests related to machine capacity and paper properties. R&D activities generated government R&D support instead of the other way around.

3.3. Strip casting technology

Strip casting technology is an innovative steel casting technology that integrates casting and rolling; thus, reheating the steel is avoided. The original roots of strip casting technology go back to the 19th century. Bessemer, one of the founding fathers of the steel industry, applied for a patent in 1857. Between 1857 and 1975 some localized R&D efforts took place, but only after 1980 a robust and large technology network emerged, consisting of 11 micro-networks. The micro-networks had a remarkably comparable composition: often a large steel-maker and a machine supplier or engineer. The steel manufacturers took the lead and persistently invested in up-scaling the technology. Six of the 11 micro-networks are still active and three of them operate strip-casting technology on an industrial scale; they needed about 15 years to achieve this state. These three most 'advanced' micro-networks may prove the feasibility of strip casting technology within 2 or 3 years (most likely in carbon mini-mills or stainless steel firms). The other micro-networks and the steel industry in general are interested to know how the casters will perform.

The major argument for developing strip casting technology has been the need to reduce the capital intensity of hot rolling. This is especially attractive for small-capacity facilities such as mini-mills and stainless steel facilities. Bessemer was already aware of the huge capital advantages of strip casting. While potential advantages were known for more than 100 years, strip casting became the centre of casting R&D activities only when (i) conventional continuous casting (introduced in the 1950s) had been fully developed, (ii) when the steel crises in the 1970s urged less capital-intensive process technologies and (iii) when stainless steel production and mini-mills became more important. Between 1975 and 1985, technologists started looking for more compact casting technologies and the technology network emerged very slowly. The innovative technology had to be seen as an incremental improvement to the conventional production route before R&D was seriously pursued. Various national governments and the European Coal and Steel Community (ECSC) contributed 5–10% of the total R&D expenditure. In three micro-networks, R&D support was more than 40%. These micro-networks stopped R&D activities or deliberately continued only on a pilot scale. In contrast, the three micro-networks that were ahead in developing strip casting technology did not obtain any external R&D support. The effect of government R&D support on the development of strip casting technology has been minimal. Since strip casting affects the core of steel business, its development is only indirectly influenced by energy-efficiency considerations or by government R&D support.

3.4. Smelting reduction technology

Smelting reduction technology is the only recent serious contender to replace the conventional energy-intensive blast furnace that has been the dominant iron-making technology for centuries. The scientific principles of smelting reduction technology are known since the 1930s, but only from 1975 onwards, a technology network emerged. By then, the performance of other innovative iron-making technologies appeared disappointing and the need of future (capital-intensive) replacement of obsolete coke ovens became imminent. The technology network, consisting of nine micro-networks, was heterogeneous. Integrated steel manufacturers dominated only four micro-networks and the variety of technical preferences reflected the variety of other actors with other R&D experiences. Not all smelting reduction technologies are likely to improve energy efficiency; the four converter-based smelting reduction technologies that were developed by the integrated steel makers were the most promising from an energy-efficiency point of view. During the 1990s, integrated steel makers lost interest in smelting reduction technology. Conventional blast furnaces and coke ovens were continually improved and the lifetimes of the existing stock was extended. The threat that obsolete coke ovens and blast furnaces would have to be replaced (requiring tremendous capital investments) appeared less pressing. In addition, the need for additional iron-making capacity became less urgent. Three micro-networks—all initiated by integrated steel manufacturers—stopped their R&D activities altogether. The expected cost advantage of smelting reduction technology deteriorated over time. Smelting reduction technology was 'locked out' by incremental improvements in the conventional process technologies. However, the future of smelting reduction technology is still undecided. Mining firms and steel mini-mills are still interested, for instance, not because the efficiency of the process but because it provides greater flexibility in coal types used.

The major arguments for R&D were the lower capital costs and the possibility of processing cheaper coals. Reducing environmental emissions and energy-efficiency improvements were only additional reasons for integrated steel firms. Likewise, environmental regulations were not decisive in initiating R&D efforts. While R&D support enlarged the technology network by supporting processes that were likely to be energy efficient, it did not accelerate the technology development. The case study illustrates that sunk capital investments in the conventional production processes strongly constrain technological development; this considerably limits the effect of government intervention and R&D support.

4. Analysis

4.1. Actors and networks

Each of the four technology case studies tells its own story about the way a specific energy-efficient process technology developed. In this section, we will analyse the findings by comparing and contrasting the four case

Table 5
Summary of the four case studies

Case study	Sector	Number of micro-networks	Micro-networks active in 2000	Dynamics of the technology network
Shoe press technology	Paper	1	(2)[a]	Only one persisting micro-network was needed for the successful development and innovation of shoe press technology, which was a major change in the design of conventional wet pressing technology. Competing machine suppliers followed
Impulse technology	Paper	2	1	After more than 25 years, the promise of impulse technology is still debated. Government R&D support induced continued R&D activity and accelerated the development, but mainly within research institutes
Strip casting technology	Iron and steel	11	6[b] (of which 3 industrial scale)	After more than a century in which strip casting of steel was merely an idea, several micro-networks recognised and felt the economic need to pursue the development of this technology. Strip casting was the next step to improve casting and rolling of steel. Three micro-networks are at the point of selling and building commercial-scale casters
Smelting reduction technology	Iron and steel	9	6 (of which 3 pilot scale)	The development of smelting reduction technology was undertaken by a variety of actors. Its application in integrated steel making seems to be 'locked out' by continuing improvements in the existing capital assets. There is an emerging opportunity for applying the technology in mini-mills

[a]After Beloit introduced the shoe press to the market, two more micro-networks emerged. The micro-network, that developed the shoe press, is no longer in business.
[b]Two of the 11 micro-networks merged.

studies. We will discuss the composition of the micro- and technology networks, the stages and patterns, and, finally, we will assess the contribution of R&D support. As a starting point, Table 5 provides an overview of the case studies.

Various types of actors have been involved. Fig. 4 shows their relative importance in the four technology networks. It demonstrates the different role of steel manufacturers and paper manufacturers in developing energy-efficient technology. The role of paper manufacturers in R&D was modest and in general quite passive. They waited for other actors to develop the technologies that affect the core of the papermaking process. Steel manufacturers (especially the integrated steel manufacturers) played an active role in developing both strip casting technology and smelting reduction technology.[2] General R&D statistics also reflect this difference in the role of manufacturing firms in these two manufacturing industries.[3] (See also Table 2.)

Fig. 3 also illustrates the crucial role of machine suppliers in the paper technology networks. In both case studies they delivered the innovative technology to the paper industry. One machine supplier dominated in the development of shoe press technology. In the case of impulse technology national pulp and paper research institutes had an important role, but the research institutes typically left the implementation to the machine supplier.

The two steel technology networks show more differences. In strip casting technology, steel firms took the lead. Whereas they co-operated with machine suppliers or engineering firms, the steel firms controlled the R&D activities. In the technology network of smelting reduction technology, the role of steel manufacturers is less dominant. They took the lead in less than half of the nine micro-networks. Smelting of iron was apparently also interesting for mining firms in order to add value to their raw materials. Furthermore, some engineering firms were involved who had experience in building and selling smelting technology for other non-ferrous metals. The heterogeneous composition of the smelting reduction

[2]Mini-mill steel firms do not invest in R&D themselves, but wait for others to develop process technologies. Both in the development of strip casting and smelting reduction technology, mini-mill steel makers showed interest at the moment the technology could be applied at a scale suitable for their mini-mills.

[3]These patterns of innovation are not static. In the development and successful introduction of thin slab casting technology (innovation in 1989), machine suppliers took the lead. Steel manufacturers, both mini-mills and integrated steel manufacturers, simply buy thin slab casting

(*footnote continued*)
technology. Steel experts discuss whether machine suppliers will increasingly adopt the task of developing process technologies. Because machine builders are becoming larger and larger, it is easier for them to develop high expenditure, innovative process technologies. Steel manufacturers are still rationalizing their corporate R&D departments (Birat, 1999).

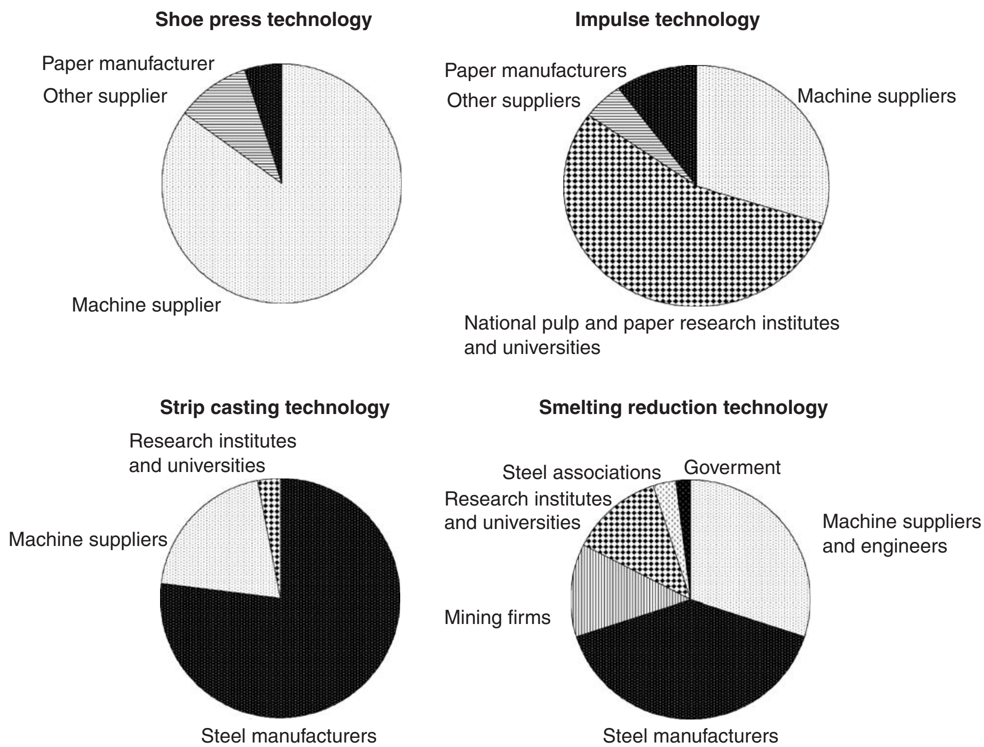

Fig. 3. Contribution of actors in the four technologies.

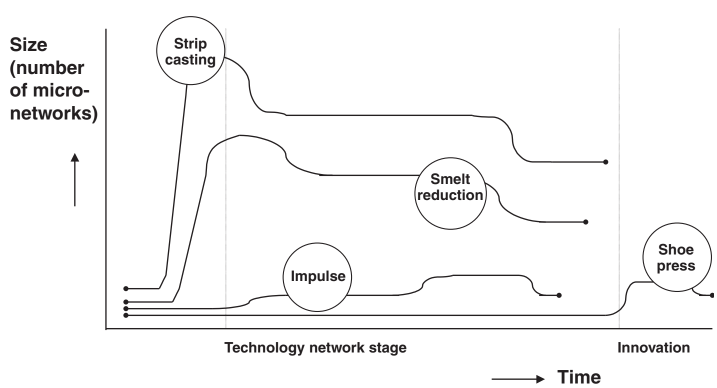

Fig. 4. The changes in the size of the technology networks in time (as measured by the number of micro-networks). The size of the four technology networks is scaled between two moments: the emergence of the technology network and the moment of first commercial application (that is not yet achieved in all technology case studies).

technology network, thus, relates to the characteristics of the technical processes involved.

The size of technology networks changes in time; see Fig. 4. The two steel technology networks are larger, in terms of the number of micro-networks, than the two paper technology networks. There are only a few paper machine suppliers and major research institutes that can initiate the required R&D effort, while there are more actors who have the financial and knowledge base to develop innovative steel technologies. Still, the total number of micro-networks—also in developing the steel technologies—is quite modest. It ranges from one to 11 micro-networks in the four technology networks (see also Table 5). It is, thus, possible to get a proper overview of the entire technology network.

The two steel technologies show a similar development in time. In both iron and steel case studies, a shake-out of efforts occurred before the technology network stabilized. Once a relatively stable technology network was in place, about a third of the micro-networks ceased their activities. This does not necessarily hamper the development of a technology. The case study of strip casting convincingly illustrates that whereas the size of the technology network decreased, the micro-networks that continued, persistently moved towards near commercial scale operation of the technology.

This leads to the question whether there is a minimum size of the technology network to ensure a reasonable chance for commercial viability. The case studies are not decisive here: the shoe press case study showed that one micro-network can be sufficient, while in the case of smelting reduction even a large network was not sufficient for success. Yet, smaller technology networks are more vulnerable. Take, for instance, the case of impulse technology: if the Swedish Pulp and Paper Research Institute had *not* managed to initiate a second micro-network in 1997, the development of impulse technology would already have come to an end.

4.2. Stages in the development

The four cases suggest a distinction between two stages: an exploration stage and a technology network stage. In the *exploration stage* the principle or the idea of an innovative technology is known and actors will more or less intensively undertake R&D activities to explore the possibilities of the technology. These activities will be loosely connected with activities elsewhere and depend on individual ambitions and means. In other words, a robust technology network has not emerged yet. The *technology network stage* takes off when the idea becomes entrenched in R&D projects and R&D agendas, and when it is a priority in R&D for several years. It is not always easy to make the distinction between the two stages. In the case of shoe press technology, for instance, one may argue that the technology network seriously emerged only after the shoe press was introduced to the market.

Why does this shift from the exploration stage to the technology network stage occur? What elements contribute to this change? The four case studies illustrate that merely evaluating the technical or economical characteristics does not suffice to understand why actors initiate and continue a technological development. Instead, we find a variety of elements that played a role in making this shift from exploration to technology network stage, which we grouped into four categories. (See Tables 6 and 7.)

A first category is that actors recognize the economic advantage of the innovative technology. This is a critical condition, but it is not sufficient. Think, for instance, of strip casting technology: while the advantages were clear since Bessemer (in 1857), the steel industry thought it was unviable during more than a century. Also, in the case of the shoe press the principle was recognized, but the majority of the actors in the paper industry did not believe in an operational solution for extending press time. Therefore, the role of the economic advantages of an innovative technology cannot be valued without taking into account other factors.

A second and very important element in Table 6 concerns the technical relatedness to the existing production process. The performance of the existing production process constrains R&D activities. For improving the competitive position of these industries (in the market in which they operate), the existing production process, which is not static either, is the starting point in searching for innovative technologies. At a certain moment, specific pressing bottlenecks may occur that require an alternative solution; an innovative technology may be recognized as an interesting solution. Alternatively, changes in the manufacturing industry's production process or in the industry itself may also facilitate the visibility of the advantages of an innovative technology.

A third category that affects the shift from the exploration stage to the technology network stage relates to the progress in R&D itself. New insights and R&D results (also in related technical areas) may enhance the confidence that the innovative idea will become an operational technology. A lost interest in other competing innovative technologies or a reduced R&D focus on the conventional technology may also contribute towards this shift. Only then, the innovative technology will be the zenith of R&D attention.

Finally, in most cases we found that other contingent factors played a role in decisions concerning R&D activities. For instance, personal contacts between people who accidentally know each other can be decisive, or the alertness of an engineer to pick up a specific idea or to bring in an old idea again. Various contingent events may

Table 6
Time frames of developing the energy-efficient technologies

Case study	Duration of exploration stage (years)	R&D started	Duration of technology network stage (years)
Shoe press technology[a]	About 15	1970	13
Impulse technology[b]	About 10	1980	More than 20
Strip casting technology	About 120	1980–1985	About 20
Smelting reduction technology[c]	About 45	1975–1985	15

[a]The time that Beloit's competitors needed for developing the technology is not taken into account because they only started developing shoe press technology when the technology was introduced to the market.

[b]Not proven yet. Impulse technology is only operational at pilot paper machines.

[c]It took 10 years to introduce the first generation Corex process to the market. This first facility was of moderate scale. It took 5 more years to prove commercial operation at double the scale of the first facility. None of the second-generation processes is operational at a near-commercial scale yet.

Table 7
The shift from exploration stage to the technology network stage

Case study	Category	Elements from case study
Shoe press technology (around 1970 and around 1980)	Economic need	Improving dryness in wet pressing has been the key for increasing machine capacity/ reduce capital intensity
	Technical need/match	The dryness out of the press became a pressing bottleneck for board grades to further increase machine capacity
	Progress in R&D	Basic studies (started around 1960) showed that the short time of pressing was a limiting factor in wet pressing. This was recognised among a wider group of engineers and researchers
	Other	Wet pressing was an important issue in Beloit's R&D agenda; freedom in R&D to look for entirely new ideas. Management support Beloit persistently initiated and continued R&D; they believed in a radically new press design whereas other machine suppliers did not
Impulse technology (1980–1983)	Economic need	Improving dryness in wet pressing has been the key for increasing machine capacity/ reduce capital intensity
	Technical need/match	—
	Progress in R&D	—
	Other	After 10 years the inventor succeeded in anchoring R&D at a pulp and paper research institute. He shelved the effort twice before; no research capacity; did not suit machine supplier' main market President pulp and paper research institute favoured the idea Beloit was eager to see how they could further improve wet pressing performance after the success of the shoe press
Strip casting technology (1980–1985)	Economic need	Linking casting and rolling leads to more compact process → cheaper iron and steel (was already clear to Bessemer in 1857)
	Technical need/match	Conventional continuous casting was a first step to make the advantages of thinner casting tangible. When conventional continuous casting matured, one started looking for technologies that could further extend the advantages Steel crises reinforced need for more compact technologies From the 1950s onwards small-scale stainless steel production had grown and mini-mill steel production had grown
	R&D	Majority of R&D focused to conventional continuous casting R&D in rapid solidification (60s and 70s) fed interest in strip casting
	Other	Early 1980s, a process took place in which mutually reinforcing factors—amongst others Allegheny's claim of success (1984)—strengthened support/interest in strip casting technology
Smelting reduction technology (1975–1985)	Economic need	More compact making process technologies → cheaper iron and steel
	Technical need/match	Threat of replacing obsolete coke ovens early 21st century (huge capital expenditure)
	Progress in R&D	For a long time coke oven/blast furnace dominated the R&D agenda Growing experience with scrap and coal in steel converters
	Other	Other small-scale innovative iron-making technologies turned out to be technically/ economically infeasible. Actors started developing smelting reduction technology as the next contender for challenging the dominant coke oven/blast furnace route for iron making

be crucial for getting things started and for showing other actors that the innovative technology is an interesting route to explore.

In our case studies the transition from the exploration to the technology network stage typically extended over a few years. During this period firms and researchers acknowledge that the innovative technology may be an interesting 'next-step-to-take' (see Table 6). We found that there is no single trigger that explains the shift to the technology network stage; a combination and mutual reinforcement of factors are needed for the technology network to emerge. The dynamics in the pulp and paper industry and the iron and steel industry are strongly constrained by the sunk capital investments in the conventional production facilities: firms tend to optimize the conventional production route rather than renew the entire system. Innovative technologies are only recognized as a next-step-to-take when an innovative technology falls within the set of options of improvement that are economically attractive, technologically feasible and compatible with the conventional production route.

4.3. R&D support

In all four cases governments tried to stimulate energy-efficient technologies, developments, in different degrees

Table 8
R&D expenditure and government R&D support[a]

Case study	Number of micro-networks	Supported micro-networks	Total R&D expenditure (M US$)	Government R&D support (M US$)	Government R&D support (%)
Shoe press	1	0	5	—	—
Impulse	2	2	35–40	15	40–45
Strip casting 1	11	6	500–700	40	5–10
Smelting reduction	9	9	550–650	165	25–30

[a]Government R&D support includes support from the Research Technology and Demonstration (RTD) programme of the European Coal and Steel Community (ECSC).

Table 9
Effect of government R&D support: additionality, acceleration and effectiveness

	Additionaliy (in # of micro-networks)	Acceleration	Effectiveness
Shoe press technology	—	—	Shoe press reduces steam consumption in drying section. Amount of energy-efficiency improvement is machine specific
Impulse technology	2	Yes	Whether an improved energy efficiency will result is uncertain (and debated)
Strip casting technology[1]	3	No	Results in improved energy efficiency. Is not likely to replace entire casting + rolling stages in integrated steel mills
Smelting reduction technology	5 all processes, 3 energy-efficient processes	No but did enlarge technology network	Some processes are likely to be more energy-efficient than blast furnace plus coke ovens + agglomeration. If implemented in mini-mill (and replacing scrap), specific energy consumption will increase

and with various outcomes. In this section we will present and discuss the role of governments investments (Table 8).

In general, government R&D support can have various effects. In our evaluation we distinguish three dimensions:

(i) *Additionality*: R&D support is additional if actors would not have started or continued R&D activities without government R&D support. This, of course, is not to say that the supported R&D activities are important and fruitful.
(ii) *Acceleration*: R&D support may result in an accelerated development of the technology in the entire technology network. Additionality is a condition for acceleration.
(iii) *Effectiveness*: R&D support is effective if it leads to an improved energy efficiency. This is achieved only when the technology is implemented and the firm-specific specific energy consumption is reduced.

Table 9 summarizes our findings of the effect of government R&D support in developing the four energy-efficient technologies.

4.4. Shoe press technology

In developing shoe press technology, the machine supplier's attempt to acquire US government support for covering the risk of innovation was never realized. Both additionality and acceleration would have been minimal, since the machine supplier was eager to introduce the shoe press.

4.5. Impulse technology

The R&D support of various national governments accelerated the development of impulse technology; the emergence of the technology network and the materialization of the technology would be less substantial without government R&D support. How did government R&D support accelerate the development of impulse technology? The technology network was not strong and this provided an opportunity to support additional R&D activities. Furthermore, government support was granted primarily to the major pulp and paper research institutes, which are more often depending on external support for initiating and continuing R&D activities. The facts that the major pulp and paper research institutes maintained close relationships with machine suppliers and that R&D activities were supported by the institutes member companies were an indication for the government that impulse technology was an appealing innovative technology. Finally, the relations and co-operation between the actors within the micro-networks made it possible for actors to benefit mutually from capacities and research facilities. In spite of all this, the case study of impulse technology clearly illustrates a major risk of government R&D support: financial support may become the dominant driver. The researchers continued to attract government financial support by claiming an improved energy efficiency. Government was patient and persistent in granting support. Even Orloff (2000), the leading impulse technology researcher at the US pulp and paper research institute, raised the question whether the research institute's R&D activities should have survived for such a long time. There are also critical questions whether the current design of impulse technology will become operational at all. Whether R&D support was effective—leading towards an improved energy efficiency—remains to be seen.

4.6. Strip casting technology

In contrast, the three micro-networks which are ahead in developing strip casting technology hardly received government R&D support. One of these three micro-networks did receive support from the ECSC during the early stages. However, this support was not additional. The contribution of government R&D support as part of the total expenditure of a micro-network and the additionality of government R&D support was largest in micro-networks that were *not* operating at the frontier of the development of strip casting. The effect of government R&D support has been minimal, because the development of strip casting was robust on its own.

4.7. Smelting reduction technology

Government R&D support enlarged the technology network of smelting reduction technology. The US and Japanese national governments and the ECSC support did have an additional effect in three micro-networks that invested in smelting reduction processes that are likely to be energy efficient. Roughly, 90% of the government R&D expenditure was spent in these three micro-networks. At this moment, only one of these three micro-networks, the Japanese, is still active, while another micro-network achieved a similar degree of materialization without government R&D support. The future plans of both micro-networks are still uncertain. Government R&D support did not accelerate the technological development, thus far.

5. The momentum of slow technology

In this study we analysed the dynamics of four technologies that promise to contribute to a more sustainable production in energy intensive industries. We used a two-level analysis: the micro-network and the technology network that comprises the interlinked activities within various micro-networks. The four case studies show that the effect of R&D support cannot be determined without an understanding of the total technology network. We will conclude this article with an analysis of the dynamics of the technology network and how it affects R&D support.

When a technology network has emerged, an innovative technology is less vulnerable to sudden changes and drawbacks. It is no longer dependent on a single actor and has, as it were, gained a life on its own. We propose to use the term 'momentum' to capture this robustness of the dispersed R&D activities related to an innovative technology. A technology network with a large momentum is less vulnerable for changes in parts of the technology network or for obstacles. Or, in other words, a technology network has a large momentum if the elements making up a technology are continuously, increasingly aligned (Callon et al., 1992).

The concept of 'momentum' is a key characteristic of a technology network (Tsoutsos and Stamboulis, 2005). The momentum is large if actors invest steadily and regularly in the development of the technology. It also reflects the confidence of actors in the prospects of the innovative technology. It is crucial for the continuance of R&D efforts that the actors involved are confirmed and reconfirmed in their expectations on the promising performance of the innovative process technology. To conclude, the momentum of a technology network is large when (i) a gradual but continuous up-scaling of the technology takes place, (ii) actors are convinced of the feasibility and the advantages of the technology, (iii) the technology network is relatively independent from other innovative technologies of improvements to the conventional production process.

Note that we use the concept momentum to characterize the technology network, in contrast to the use of the term in studies of large technical systems, such as the electricity system. Hughes (1983, 1987) coined the term to account for the growth of a large technical system that consists of highly interrelated technical and socio-organizational components. Hughes claimed that when such a system grows and consolidates, the total 'mass' of technical and socio-organizational components possesses 'direction' and displays a rate of growth, suggesting velocity. The whole system expands at a certain pace and has a 'momentum'. According to Hughes (1987) some components fall behind during the growth of a system, i.e. so-called 'reverse salients' appear. These are translated into 'critical problems' that have to be solved in order to continue the growth of the system. In such an expanding system, 'system builders' involve other actors. In contrast, we use momentum in the context of 'slow' technology: a mature process industry that is bound to optimize its overall performance. Here the development of innovative technologies occurs within the restriction of the existing production process and within a—most often—established set of business and R&D linkages among actors who have a reputation in developing or delivering process technologies. In addition, the number of competing alternative innovative technologies is restricted.

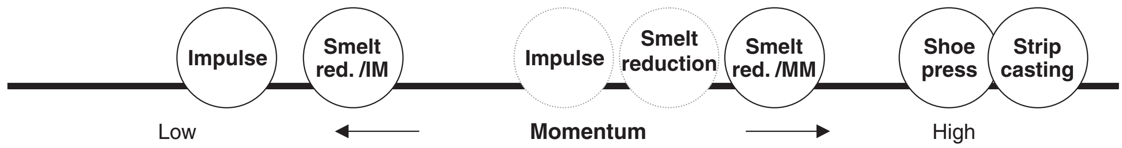

Fig. 5. The four technology networks ranked according to their momentum. The dotted circles indicate the former momentum. Note that the application of smelting reduction technology bifurcated: integrated steel makers lost interest, while application in mini-mills is a likely next step.

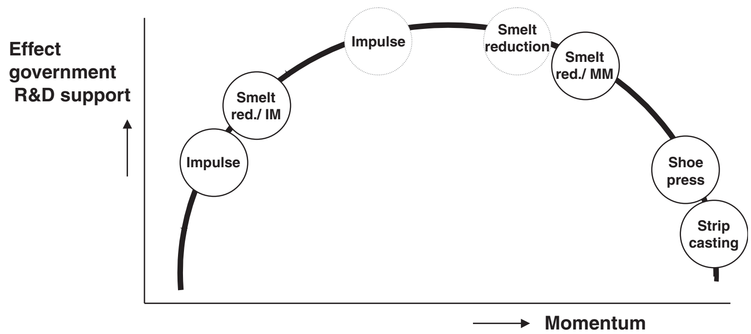

Fig. 6. The effect of government R&D support as a function of the momentum of a technology network.

The analyst can assess the momentum of a technology network with two interrelated methods. The first method is to consult experts involved in the development of a specific technology. Often experts use the concept of momentum themselves in their assessments of the future use and performance of a technology. The second, complementary, method is to review (i) the continuation of R&D activities, (ii) the status of the innovative technology as the next-step-to be developed, (iii) the expressed confidence in the performance of an innovative technology, (iv) the progress made in up-scaling the innovative technology. We used both two methods in the case studies. See Table 8 for an assessment of the momentum in the four case studies (Fig. 5).

In our studies we found that it is crucial for maintaining momentum that the technology remains the next-step-to-take. The promising perceived performance characteristics have to be confirmed and reconfirmed. In a similar way, actors must not lose confidence in the future adoption of the innovative technology. The two most smoothly developed technologies encountered the least doubt regarding the future performance. R&D activities are performed against the backdrop of R&D activities within the entire technology network, of further technological developments in the traditional production process, and against the backdrop of trends and changes in the industry at stake. The confidence in the future perspectives of a technology depends on R&D results, claimed successes by other micro-networks, major technical difficulties, and difficulties in commercializing the technology. The role of established firms appears very important here, as their reputation helps to have the technology accepted as the next step to take.

We found an interesting relationship between the momentum of the technology networks and the effectiveness of R&D support: an inverted U (Fig. 6). When the momentum of the technology networks is high, as in the cases of strip casting technology and shoe press technology, R&D support does not accelerate the technological development. In such circumstances, it is difficult to intervene effectively since government support does not lead to additional activities. When the momentum of a technology network is low, as in the case of smelting reduction technology and impulse technology, R&D support does not contribute to a sustained and viable series of R&D activities either. The government R&D support may lead to additional R&D activities in various micro-networks but will not result in a robust technology network. The inverted U of Fig. 6 shows how the momentum of a technology is critical for the effectiveness of R&D support.

6. Conclusion

The thrust of our research is that the effect of government intervention depends on the dynamics of the technological network. Intervention strategies need to be fine-tuned to the peculiarities of the manufacturing industry and to the technology networks of energy-efficient technologies. This brings us to the following recommendations on government R&D support in the case of industrial process technologies. First of all, decisions about R&D support of industrial energy-efficient technologies requires an assessment of the momentum of the (international) technology network. This, in its turn, requires an understanding of the actors (investments in R&D, arguments, competitive relationships), of the technology networks (reputation and capacity of actors involved, patterns), and of the technology itself (relation to the traditional production process, claimed performance characteristics, timeframe of the R&D trajectory). Such information is needed to assess the viability of government intervention. For instance, do national governments have access to the actors that can make a difference in international technology networks?

It also follows from our analysis that the timing of intervention matters, as the momentum of a technology network will change over time. Whereas the emergence of a technology network may require support, a continued support for more than 10 years is much less likely to be sound. Therefore, it is important to increase monitoring efforts, both for decisions whether or not to start government intervention, but also to evaluate (ex post) the effect of intervention strategies. Acquiring and maintaining information on technology networks and energy-efficient technologies requires a continuous investment in monitoring activity. It will be helpful to join forces internationally in these monitoring efforts (e.g. within the IEA), as all national governments benefit from the information made available.

Finally, governments should better protect their own agenda in terms of its primary interest, i.e. energy efficiency. While an innovative technology may be energy efficient, other promising performance characteristics may have priority within the manufacturing industry. The impulse technology case is a clear example: energy efficiency was claimed to justify R&D support, but was not the major focus in the actual R&D activities. Again, an understanding of the technology networks and the dynamics of technological development will help to improve the effect of government intervention in the field of industrial energy efficiency, R&D and innovation.

We conclude that whereas government R&D support is the most popular policy instrument in stimulating the development of energy-efficient technologies, it is also a rather weak instrument, since it cannot determine the outcome of technological development. The effect of R&D support depend on the actors in the industry: on their intentions, their plans, their embeddedness in a network of actors, their own R&D investments, their strategic business decisions, and their efficiency in doing something valuable with the financial R&D support. Yet, R&D support can be a valuable and decisive instrument, provided the underlying dynamics of 'slow' technologies is sufficiently taken into account.

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