Innovation Systems and European Integration (ISE)

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Sub-Project 3.2.2: Government Technology Procurement as a Policy Instrument

Shaping the Tools of Competitive Power: Government Technology Procurement in the Making of the HVDC Technology

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Abstract:
The study describes and analyzes the development and commercialization of the Swedish High-Voltage Direct Current (HVDC) technology that was a result of a Government Technology Procurement (GTP) project 1940-65 between the private Swedish electrotechnical company ASEA as the producer and the governmental agency Swedish State Power Board acting as an active lead user. The most important global and local changes that influenced the user and the producer before and after the formal procurement project are analyzed. The description of the innovation process closes when the HVDC reached commercial maturity locally and globally and passed through its first Adaptive Government Procurement. The GTP process is analyzed by dividing it into the three phases of Proto-Procurement 1919–39, Procurement 1940–54, and Post-Procurement 1950–65. In the Proto-Procurement Phase is discussed the creation of technological diversity among possible HVDC proto-technologies, the formation of Swedish and international proto-demand among potential power users, the importance of innovational learning processes among the user- and producer-to-be, and the creation of absorptive capacity and social trust. The focus in the Procurement Phase is on the Swedish selection of the successful HVDC technology through a Developmental Government Procurement project. The project is analyzed by looking at the formation of bridging or linking institutions through joint project groups and development projects. Furthermore, various critical technical and organizational problems and their solutions are analyzed. Also the first commercial HVDC installation is described. In the Post-Procurement Phase the HVDC technology has matured and a description is given of how new markets were developed and especially how the first successful technology transfer abroad was accomplished, an example of successful AGP. Finally is given a cost-benefit of the project and a discussion of policy issues.

Key-words: Technology Procurement, Electric Power, HVDC, User-Producer Interaction, Social Trust, Interactive Learning, Sociotechnical Shaping, Reverse Salients, Development Pair

1. INTRODUCTION: The Sociotechnical Shaping of Procurement

This is a study of the procurement of the High Voltage Direct Current (HVDC) electrotechnical transmission technology. Partly thanks to HVDC the Swedish-Swiss ABB company is today one of the most competitive electrotechnical companies in the world and the Swedish government can through its company Vattenfall (formerly Swedish State Power Board, SSPB) compete on the European power market with cheap electric power. Furthermore, this is today probably the most important tool for integrating different national electric power systems in Europe as well as in the rest of the world. An aspect maybe in itself interesting enough to justify a study in a research project concerning innovations and European integration.

The major aim of this study is to investigate the processes that created the tool for this European competitiveness. This was an example of very successful Government Technology Procurement (GTP). If we wish to gain a better understanding of how innovations are shaped in procurement processes we have to use longitudinal studies of innovations. Here this is accomplished through the developmental history of the procurement of HVDC technology.

In this study the two phenomena of Government Technology Procurement and Development Pairs are of central importance. Both of these are examples of sociotechnical procurement processes and both of these have been of central importance to Swedish industrial development.

1.1 Introducing Government Technology Procurement

Government Technology Procurement (GTP) is the name used to describe the process when a government orders a technology that demands substantial development work before it becomes functional.[1] The technological activities that enter under the term GTP can be placed on a spectrum between the two poles of *creation* of a technology called *Development Government Procurement* (DGP), and the *transfer* of a technology, *Adaptive Government Procurement* (AGP).

DGP are procurement processes where *the majority* of the innovation activities concern the development of a new technology, and AGP are procurement processes where a substantial amount of the innovation activities are centred around adapting already existing technologies to new use-environments.

What is interesting for this study is if the *core activities* in the procurement process is concerned with creating a new technology or with adapting an old to a new use-environment. The case of the development of HVDC is especially interesting since it is an example of an procurement process which contains both versions of GTP. In the second phase of the procurement process the *Development* GP and in the third and last procurement phase the transfer-oriented *Adaptive* GP is described.

1.2 Introducing Development Pairs

A *Development Pair* (DP) is the name given to the several examples of long-term user-producer relations that has existed in Sweden between government agencies and large industrial firms. These has been tightly linked cooperative relationships between a government customer and a manufacturing firm and has grown out of a chain of several joint development projects[2] In Swedish history there are several examples of DP's in the form of long-term collaborations on the development of new technologies between large Swedish engineering companies and government technical agencies. Among those most well known are the Ericsson company and Swedish Telecom and their joint development of telecommunications technology, ASEA's (today ABB) and the State Power Board's collaboration on electric power technology, SAAB and the Defence Material Administration collaborating on aircraft technology, and ASEA and the State Railway Agency working on train technology.[3]

The government user in a DP is a customer that uses the manufacturing firm's products in its professional activities. The user many times functions as a *lead-user*. These are advanced users that are especially favourable to innovation then they face needs before most other users and because they are in a position to benefit significantly by obtaining new solution to their needs.[4] In this way a the two parties of a DP function complimentary towards each other, bringing together advanced needs and advanced means and forming a *collective innovator* since the focus of the innovational activities shifts between the two parties depending on the stages of the innovation process and on what innovation activities that are performed.

Development Pairs can be seen as being close to the model of the "Developmental State" formulated by Chalmers Johnson.[5] This model has been used to explain the development of such competitive nations as Japan, Taiwan and Korea and describes a state structure focused on industrial developmental goals based on close relations between state bureaucrats and private industry around industrial transformation. This model has four main elements: a small elite bureaucracy directed towards industrial transformation, a political system in which the bureaucracy is given ”sufficient scope to take initiative and operate effectively”, the ”perfection of market-conforming methods of state intervention” in industry, and the existence of a pilot organisation like MITI in Japan.[6] The model has been developed further by Peter Evans to explain the following about the connections between the developmental state (the government bureaucracy) and ’outside’ society:

> ”Highly selective meritocratic recruitment and long-term career rewards create a commitment and a sense of corporate coherence. Corporate coherence gives these apparatuses a certain kind of ’autonomy.’ They are not, however, insulated from society [...] they are embedded in a concrete set of social ties that binds state to society and provides institutionalized channels for the continual negotiation and renegotiation of goals and policies. Either side of the combination by itself would not work. A state that was only autonomous would lack both sources of intelligence and the ability to rely on decentralized private implementation. Dense connecting networks without a robust internal structure would leave the state incapable of solving ’collective action’ problems, of transcending the individual interests of private counterparts. Only when embeddedness and autonomy is joined together can a state be called developmental.”[7]

There are both similarities and differences between DP and GTP. One major difference is the time span. Where a DP is normally an industrial relation that has developed informally over tens of years, a GTP project usually but not exclusively has a more formalised and short-term character. Also, the joint activities in a DP are in general more diverse than those in a GTP, i.e. it includes joint development of different magnitude and time span such as informal day-to-day technical exchange activities, technical improvement projects on delivered process and product technologies, large-scale experimental and long-term R&D activities, as well as including formalised GTP projects.

1.3 Sociotechnical Shaping of Procurement Processes

The GTP process is analyzed as a longitudinal sociotechnical process where the outcome are shaped by tightly coupled social and technical factors. Following

Martin Rudwick the procurement process is analyzed as ”ineluctably and intrinsically *social* in character, not (or not primarily) in the sense of the pressures of the wider social world, but in the sense of intense social interaction among a small group of participants.”[8]

The method of analyzing its sociotechnical character is to follow a procurement project *in-the-making* i.e. in the description of the procurement process try to reconstruct its inherent diversity by emphasizing the diversity and openness by including alternatives that were actively or passively deselected by the participants or the environment.[9]

In the analyzing process it is necessary to ”shelve any knowledge of what was for the participants an unknown future in order to reconstruct the processes by which they were later to reach it.”[10] If not, a lot of the openness and uncertainty will be lost to the analyst and there is a large risk of presenting a flawed description giving the impression of the innovation activities being directed in a linear fashion. It is important to emphasise this complexity to get at the factors that are salient in innovation processes.

1.4 Practices of Innovation

Another aspect of the innovation process that is important to understand is the actual *innovation practice*, i.e. how the process of problem construction (formulation) and problem solving is sociotechnically construed on the micro-level.[11] Two factors of the praxis of innovating that becomes visible through micro studies of practice are the importance of ”technological salients” in problem construction and ”interactive learning” in problem solving.

1.4.1 Technological Salients as Innovation Focusing Devices

The term *Technological Salients* (TS) are introduced as a compound term for the twin concepts of *salients* and *reverse salients*, introduced by Thomas P. Hughes.[12] A salient is a sociotechnical component in an expanding technological system that is perceived as being more advanced, efficient or economical than the rest of the components in the system, and a reverse salient is a component that is identified as ’lagging behind’ the front of the system and through this is perceived as slowing down or stopping the system in its furthering towards its system goal.[13] Technological salients are important as ’focusing devices’ for technological change then a lot of the activities of engineers and other system builders involved in developing technological systems are centred around the social construction of technological salients.[14]

This social construction of technological salients are mainly through three different levels of construction: indirectly through constructing *system goals*, directly through constructing *technological salients* and through breaking down technological salients into one or several *critical problems*.

System builders socially construct technological salients in two major ways. First through the *construction or re-construction of the system goal* with its following redefinition of technological salients, and secondly in that system builders *identify social or technical components* in a technological system that are perceived as increasing or opening up (salient) or slowing down or blocking (reverse salient) the furthering of the system towards its goal.[15]

After a technological salient has been identified the binary terms of *utilisation-elimination* become central in the process when those aware of its salient character then go about – in the case of a salient – propagating its usefulness (the ’opportunity’ that is now there for those that ’see’ to take it) and either try to utilise that themselves or encourage others to do so through further innovational activities, or – in the case of a reverse salient – in the same way go about propagating its general ’backwardness’ and try to eliminate it by developing it further. The third layer of the practice of the construction of technological salients is when the utilisation-elimination of an identified *technological salient is operationalized through the formulation and solution of ”critical problems”* of a more practical technological or organisational nature.

1.4.2 Interactive Learning in Innovation

The second major aspect of technological praxis of procurement investigated here is that of *interactive learning*. This is a compound term meaning that the technological knowledge used in innovational processes are based on different learning processes.

That knowledge is a result of learning can sound like stating a truism but the interesting and not so obvious fact is that much of this knowledge and learning is of a *local* character, i.e. it exists in the form of embodied and tacit knowledge in a firm’s personnel and is created in and through specific processes of manufacturing, operating and developing certain technologies. Some of this new knowledge can be disembodied and put down in articles and books and transmitted and learnt that way but a lot of this knowledge are of a complex and non-theoretical character and must be learnt through first-hand knowledge of operating and testing the material artefacts. The three learning processes that is going to be investigated here are learning-by-doing, learning-by-using and learning-by-interacting.

Learning-by-doing is used to denote a producer's new technological knowledge of how to operate a (manufacturing) technology in a more efficient way. This knowledge is created in and through the process of operating the technology. This knowledge can later be used to improve the technology further.

Learning-by-using is in many ways very similar to learning-by-doing.[16] This process comes after learning-by-doing in that it starts only after a new product has been put into use. This new knowledge can lead to alterations in the use of the product *or* to smaller or major improvements in the design of the product. Through this the active participation of the user is brought into the innovation process and the focus on innovative manufacturers is shifted to innovative users.

Learning-by-interacting is describing the new knowledge that is created among (industrial) users and producers in the process of developing complex product innovations through user-producer interactions. The development of complex products always includes a great deal of uncertainty and risk for the user as well as the producer. This demands a mixture of formal instrumental and strategic rationality with more informal communicative rationality. This mixture of rationalities is typical for the DP type of user-producer interaction. According to Lundwall innovation projects are characterised by a combination of aspects of strategic and communicative rationality, which explains

> why firms might engage in far-reaching interfirm cooperation in uncertain and costly innovation projects without a formal contractual basis. Within and between firms, the existence of subspheres dominated by communicative, rather than strategic, rationality may be an important explanation of the existing institutional set-up.[17]

The last important aspect of innovation practice that is most relevant to this study is the creation of *absorptive capacity*. This is ”an ability to recognise the value of new information, assimilate it, and apply it to commercial ends” and it is developed through previous experience of knowledge and practice related to the new information that is going to be used in the innovation process.[18] Absorptive capacity can ”be developed as a by-product of a firm's manufacturing operations” and such ”direct involvement in manufacturing” makes a firm ”better able to recognise and exploit new information relevant to a particular product market.”[19] In the GTP case studied this came from learning among the manufacturer (ASEA) in the process of incrementally improving an already existing commercial technology (the Mercury-Arc Rectifier).

1.5 The GTP Process: The Short Story

The development of the Swedish HVDC technology that was inaugurated 1956 was a result of a GTP project between the Swedish electrotechnical company ASEA and the Swedish State Power Board that started in 1940.[20] However, the development of the HVDC technology did neither started nor ended with the procurement process for that project.

Therefore the study analyzes the most important global and local changes in connection to HVDC that influenced the user SSPB as well as the producer ASEA before and after the formal procurement project. The description of the innovation process closes when the technology has reached commercial maturity locally and globally as well as having gone through its first AGP. Therefore the GTP process is divided into the three phases of Proto-Procurement, Procurement, and Post-Procurement. Despite, the linear appearance of the procurement process it is important to remember that this division is made for analytic purposes and does not resemble any actual perception of the actors since it is constructed after the procurement project has proved to be successful.

In the *Proto-Procurement Phase* is discussed the creation of technological diversity among possible HVDC technologies, the importance of innovational learning processes and the creation of absorptive capacity and social trust. The focus in the *Procurement Phase* is on the Swedish selection of the successful HVDC technology through DGP. Finally, in the *Post-Procurement Phase* the technology has matured and a description is given of how new markets were developed and especially the first successful technology transfer abroad which was an example of successful AGP.

An interesting aspect of this way of describing the HVDC case is that it gives an example of both the creation- (DGP) and adaptation-oriented (AGP) poles of Government Technology Procurement processes.

2. PROTO-PROCUREMENT: In Search of New Power and New Products

In retrospect the period 1919-1939 can be said to be a formative period for several crucial procurement resources globally as well as locally.

When it comes to *demand* for the innovation-to-be, discussions among the international engineering community generated proto-demand in the form of several potential super power transmission projects suitable for HVDC transmissions and created a familiarity with the critical problems of the future user, the Swedish State Power Board (SSPB). In the period when it comes to *supply*, globally novelty and diversity was created among HVDC proto-technologies and locally an absorptive capacity was created of the future producer ASEA.

Last but not least the period saw the structuring of international relations in the electrotechnical sector in that the petty giant ASEA gained an international respect among the large international firms and locally in Sweden the DP between ASEA and the SSPB had matured. After a 20-year long period of social learning in different user-producer projects a mutual social trust had been developed that became important in the following Procurement Phase.

2.1. Prelude: The Battle of the Currents

The 1880s and 1890s saw the ”battle of the currents” between Direct Current (DC) and Alternating Current (AC) technologies about which was the most competitive technology for long-distance transmission of electric power.[21] The pioneering low-voltage DC technology met increasing competition from AC technology because of very large cable costs for transmitting low-voltage DC more than couple of kilometres. AC technology could, unlike DC, transform power between low and high voltages and therefore had the advantage of using high voltage electricity for transmission and less dangerous low voltage when the electricity was put to use in lamps and motors.

There was a strong and early interest among European firms in long-distance transmission of power. To test the commercial feasibility of AC a long-distance power transmission was set up by German and Swiss firms in 1891.[22] The test was a success for AC, but also DC developed further through the Thury High Voltage DC (HVDC) transmission technology. The battle of the currents was still undecided and as these projects went on line, there were discussions concerning the first large project to transmit power over long distances. This was the building of the world's largest power plant at Niagara Falls in US. An advisory commission first recommended to use high voltage DC. But as the experience of AC increased, the commission's opinion swayed to a decision in favour of high voltage AC.

In 1896 Niagara started producing hydro power and demonstrated the possibilities of large-scale production and long-distance transmission of electric power and the value of AC ”in bringing into service remote waterfalls hitherto running to waste.”[23] This decided the battle of the currents and created a hegemony of the AC technology for long-distance transmission that was going to keep its hold until the ”second battle of the currents” in the 1920s.[24]

2.2 Shaping the Needs: Developing Proto-Procurement

In the 1920s discussions started about transmissions of larger amounts of power over distances of more than 200 km. This identified reverse salients of a new dimension for AC-technology. Mainly, these were the critical problems with the electrical stability of the power lines, and the impossibility of building long underground or undersea cable lines. As a solution to these critical problems, engineers put forward HVDC transmission, which did not have any of these problems. Also, HVDC promised to be less expensive.

2.2.1 Global Proto-Demand: Plans for International Interconnections

The interwar period saw a rising demand for power reflected in discussions of several international ”super power transmissions” – long distance transmissions of large amounts of power. AC and DC once again competed against each other. The largest and most seriously contemplated was projects of exporting electricity from the rich Norwegian hydro power sources to the European continent.

After WWI The Danish government contacted the Norwegian and Swedish governments concerning the possibility of a power transmission from Norway through Sweden to Denmark. Denmark relied almost exclusively on steam power and the war had demonstrated the country's large dependence on imported coal. As a remedy, the idea of increased Nordic electric power exchange had been put forward.[25] Norway had one of the world's largest hydro power resources with waterfalls inexpensive to exploit and with only a limited domestic market potential.

A joint Nordic commission with representatives from SSPB was appointed to investigate technological and economic problems in connection with such a super power project. The commission put forward a report that showed the feasibility of a 40.000 thousand watt (kW) Inter-Scandinavian power transmission with AC or HVDC but no decision was taken. The discussion around the Inter-Scandinavian project and other several plans for inter-European power grids continued in the 1920s and again in 1930 in connection with plans to export Norwegian power to Germany.[26] However, the world economic crisis of the 1930s made these large projects unrealistic because power producers suffered from lack of demand.

In Germany with the coming of the Nazi take-over in 1933 the power sector began to reinforce its national power grid to be able to put up defence measures in case of a new European war. In connection with this the German military became interested in super power and cable transmission projects.[27] Also in Russia there were discussions of large plans for national super-power transmissions.

2.2.2 Local Proto-Demand: Plans for a National Grid

In Sweden, the major actor in the electric power system was the State through the SSPB. There is no state monopoly on the ownership of hydro power or electricity generation in Sweden and large and small privately or municipally owned power companies competed with each other and with the SSPB for customers. The distribution in the major cities to its electric lighting, tramways, households and industries was usually handled by municipal utilities. They in some cases owned their own coal and hydro power plants or bought electricity from other power companies or SSPB. The largest power producer in Sweden with four large power plants was SSPB that was in charge of exploiting the hydro power that belonged to the Swedish state. In addition to SSPB three other power companies owned interest in trunk lines for voltages of 220.000 volts and therefore had interest in super power transmissions: Krångede AB, Sydsvenska Kraft AB (Sydkraft) and Stockholm’s Electricity Utility. Among the smaller utilities was SEV that was owned by the electrical manufacturer ASEA. This company was going to become important for the development of the HVDC technology.

During the interwar period SSPB connected the power networks of its two regional hydro power plants in central Sweden to each other and it was the first step in a plan to create a national power grid. The grid should interconnect all of the State’s power plants from the upper North to the South into one system and through this use the different power plants more efficiently. The last of the State’s three large regional systems was in the very north of Sweden, in upper Norrland.

This system was centred around a hydro power plant at Harsprånget, Sweden’s largest waterfall. This system was isolated from the south of Sweden and at this point in time it was seen as unrealistic to transfer large amounts of power the 1.000 km to central Sweden.

In 1930 when SSPB expanded on their earlier vision of a national grid and now put forward the advantages of a country-plan for power distribution; that ”as much possible is based on *self-sufficiency*."[28] In this plan *all* of the country’s private, municipal and state power plants would be interconnected into a national power system. But SSPB’s plan got thwarted in the mid-30s when two large private power companies decided to interconnect their systems in the north and south of Sweden with an AC-transmission link. SSPB protested to the Government and a state inquiry concerning the future transmission system was appointed that recommended that further development be carried out in co-operation between SSPB and private utilities. In 1938 SSPB started to transfer power from the upper North via the privately owned power line. But this was only a small amount of all its power in the very North that laid dormant and waiting for the demand to grow enough and for the technology to progress enough for it to be possible. And this was seen as coming sometime in the 1960s.

2.3 Shaping the Means: Developing Proto-Technologies

The major reverse salient for DC transmissions was the lack of a commercially competitive method for converting between DC and AC. This conversion was necessary because the customers of electric power almost exclusively used it in machinery run with low voltage AC. The critical technological problem therefore was to develop a *converter* between high voltage DC and low voltage AC.

Several independent inventors and all the major international electrotechnical firms were competing around presenting prototypes of their respective solutions. And this competitive atmosphere between independent inventors and established firms existed both globally as well as in the local environment of the Swedish proto-innovation that was going to leave this struggle triumphant in the procurement phase.

Although HVDC is a very good example of an advanced high-technology it is not so much an example of 'technology as applied science' as an example of 'technology as applied technology'.[29] This breakthrough invention was very much an application of previous technological knowledge and a good example of the importance of ”absorptive capacity” developed through previous industrial practice.[30] In this proto-procurement phase this ’application of technology’ comes from many small bits and pieces of technological knowledge and resources accumulated in the normal industrial processes of incremental improvements on an already functional standard technology. This is a very good example of how absorptive capacity is developed as a by-product of a firm's manufacturing.

2.3.1 Global Search: Creating Technological Diversity

In 1919 there already existed a functioning technology for HVDC. This was the so called Thury or Series system that had shown itself "notoriously successful" and had proven the technical and commercial possibility of long distance HVDC transmission with a 180 km long HVDC transmission of 19.000 thousand watts (kW) effect in France.[31] However, the existing electromechanical rotary converters used in the Series-system were regarded as too clumsy and costly. However, at the same time there had started to appear new more promising electrical solutions to the DC converter problem. The first one had come from England.

The Empire Takes the Lead: The Transverter

In 1922 a new British converter was announced to the public. This was the Transverter that was a further development of the rotating machinery used in the Series system and in 1924 at the British Empire Exhibition the company English Electric created a lot of attention with a demonstration of an Transverter with a capacity of 2.000 kW.[32]

The States Strikes Back: The Thyratron

Since the early 20s the American giant General Electric Co. (GEC) had been doing research on HVDC transmission with the hope of being able to develop a long-distance ”superpower transmission system”.[33] Their converter was based on their Thyratron mercury gas triode tube. In 1929 GEC announced that they had also succeeded in developing a new converter. In 1931 GEC stated that there existed no theoretical reasons against HVDC transmissions with the new converter and the English Journal The Electrician reported that the battle between AC and DC ”seems to be entering upon a new and most interesting phase”.[34]

A Challenger from the Continent: The Mercury-Arc Rectifier

The same year the German Siemens (SSW) company could report that they had further developed their Mercury-Arc Rectifiers (MARs) so that they could be used to convert from DC to AC and it seemed like this was the ”apparative Lösung” of the critical problem of HVDC transmission and SSW said that they were ready to build HVDC transmissions.[35] Also the other major German company AEG let it be known that they pursued development work on Thyratrons for HVDC transmission.

In Service of the Reich: The Airblast Converter

In May 1932 yet another converter was presented to the public. This converter was going to experience the probably largest expectation in the 1930s. This was an Air Pressure Rectifier developed by the famous scientist and independent inventor Erwin Marx.[36] Marx wanted to use his invention to further the German war effort. HVDC transmission with underground cables was of great military interest because AC power lines were disturbing to airfields and made industrial plants very easy to find from aircraft.[37] Marx's airblast converter became a secret defence project, but in 1937 it became clear that this technology was a dead-end and the German electroindustries restarted their other converter research.

Contenders from the North: The Glesum System and the Ion Valve

In addition to this two new Swedish converter technologies were presented. The first was the so called Glesum system by a famous Swedish independent inventor with the help of a professor at the Royal Institute of Technology in Stockholm. The Glesum-system was publicly presented at a meeting in 1934. And at the same meeting an additional new converter technology – an Ion Valve – was presented when an engineer from ASEA ”gave the sensational announcement” that the company was working on a HVDC transmission system based on the MAR technology. The following day one of the major daily newspaper announced on its front-page: ”High voltage direct current also from ASEA: von Platen's system gets Swedish competitor”[38]

Survival in the Field: HVDC in Trial Transmissions

In the mid-30s GEC conducted the first field tests of HVDC transmissions with small-scale experimental converters of 3.000 kW. The experiments ”exceeded expectations” and the company said that it planned experimental transmissions of more realistic transmissions.[39] In 1939 an HVDC transmission was publicly demonstrated for the first time when the Swiss company Brown Boveri & Cie (BBC) used their Mutator converter to transmit DC around 20 km. Even though the transmitted effect was only 500 kW BBC claimed that ”doubt can no longer exist” that economical super power transmissions would be by HVDC and they intended to go ahead with higher effects.[40] However the Swiss demonstration was stopped with the outbreak of WWII.

2.3.2 Local Search: The Shop-Floor as a Learning Laboratory

When it comes to Swedish manufacturers in electrical technology, ASEA was the most important Swedish company. Regarding high voltage technology after the 1930s, except for ASEA and its subsidiaries the only independent Swedish company was the cable manufacturer Sieverts that was controlled by the Ericsson company. Also the German and Swiss electrotechnical giants Siemens, AEG and Brown Boveri (BBC) was also active in Sweden through Swedish subsidiaries and representatives.

In the end of 1925 the management of ASEA's management decided that the company was going to start selling low-voltage Mercury-Arc Rectifiers (MAR) used for converting AC to DC. This was because the use of DC expanded in the 1920s mainly depending on the growth of the old urban DC-networks used for lighting and tramways. The DC needed for this had been generated through conversion of AC by traditional mechanical rotary converters but since 1904 the electrical MAR had become a serious alternative. At the turn of the century all the large European electrotechnical companies manufactured MARs with BBC as the leader. The first MARs were made of glass which limited its use to small effects but a new range of effects had been made possible when the first commercial steel-tank MARs had been introduced by BBC in the 1910s.[41] These were more reliable, efficient and less complicated than the rotary converters that were gradually replaced in the 1910s and 1920s.

Learning-by-Trying: ASEA's first MAR

When ASEA in the 20s decided to enter the MAR-market it was a laggard and first the company discussed acquiring a license on a foreign construction.[42] But in the end it was decided to develop a more independent construction and to start manufacturing a series of commercial low-voltage MARs based on this construction. To be able to do this ASEA in 1927 wrote a contract with the consulting engineer Béla Schäfer for him to supply ASEA with drawings and advice for the construction of a large MAR.[43] Schäfer in 1910 had introduced a successful design of a metal MAR ”which broke away from the hitherto accepted practice of construction and was the forerunner” of the modern steel-tank MAR.[44] After that Schäfer worked for some time at BBC that developed his design ”on a commercial scale”.[45]

Schäfer supplied ASEA with drawings and advice on how to construct the MAR, drawings that ”most likely was a plagiarism from Brown Boveri”.[46] In 1928 the construction of the experimental MAR for 900 kW was finished. However, it did not function satisfactorily. It suffered from severe disturbances depending on material problem and of ”back fires”, which was short circuits caused by failure of the MAR to block the negative AC current. This was a phenomenon that occurred at random at voltages above some hundred volts.[47]

The engineer Uno Lamm was in 1928 put in charge of a group that was trying to solve the *critical problems* of the back-fires. They soon found that Schäfer's MAR was ”not capable of development in many respects” and instead went on and developed a new construction on their own. Lamm began forming a group of engineers, technicians and knowledge in MAR development.[48] Through this he had started building up ASEA's *absorptive capacity* in HVDC technology.

Learning-by-Using: A MAR of its Own

Lamm's group started by constructing a new MAR with lower effect for internal use in ASEA's laboratory. This was not an 'independent' construction since ASEA's engineers had acquired a lot of their knowledge and constructional solutions from the failed construction of Schäfer's MAR. This was also later recognised through royalties to Schäfer.

In 1930 ASEA turned to the municipal power utility in Stockholm and asked if ASEA could install a prototype MAR in some of their tramway substations to try out their new construction in real operation. The Stockholm Utility accepted.

Learning-by-Doing: ASEA's First Commercial MAR

At the end of 1930 ASEA gave in a tender for a commercial delivery of a MAR of 2.000 kW for the Gothenburg Electricity Utility. In 1932 ASEA delivered the Stockholm MAR of 1.400 kW and it worked so well that the utility took it in formal operation one year ahead of contractual stipulations. The Gothenburg MAR had more problems and had to be taken back to ASEA for adjustments. These problems in retrospect can be seen as filling an important task in giving valuable results for the further development of MARs for low-voltage and – later on – for HVDC MARs.

The management had seen it as an important task to get more reference orders and to increase their efforts in that respect. This succeeded and the next order came in 1932 ”in very hard competition with foreign manufacturers” and was to the Danish State Railways.[49] This was a very important order both because of its large size – six MARs of 2.500 kW – but also because it was the first export order and meant that ASEA's new construction was to be measured against its international competitors. The Danish Railways did not dare to give ASEA the whole order since ASEA did not have enough reference-projects to show and therefore ordered three MARs from BBC, the leading manufacturer.[50] ASEA was ”especially pleased" with this outcome and considered it very important to deliver MARs that in quality could match BBC's.[51]

ASEA's new low-voltage MARs had now reached technical and commercial maturity and in 1933 the MAR development moved away from its wooden shed on the factory shop-floor to a new large separate building.

As Lamm's group had worked on solving the problems of making a functional low-voltage MAR they had also thought about how to construct a MAR for the 50-100 times higher voltages that were seen as necessary for HVDC super power transmissions.[52] And in 1933 the first experiments towards developing a HVDC MAR were performed.

The first experimental HVDC MAR: Glesum versus the Ion Valve

The first experimental HVDC MAR was "sneaked in" between the work on the low-voltage MARs and was speeded up because of the invention of the Glesum system.[53] Since 1932 the Glesum system had been tested and further developed at the Royal Institute of Technology by a professor in electrical machinery.[54]

A new company had been formed to exploit the new invention and ASEA had been approached about investing around half a million Crowns to "acquire patents and experience". ASEA's leading engineers declared that it seemed as if the converter problem was solved and that the invention seemed to be the one that best could solve the problem with HVDC transmission. However, when ASEA considered the prospects for a large DC transmission in the next 10-20 years they looked "extremely small" internationally and non-existent in Sweden. This was because the eventual Swedish transmission from upper Norrland would "wait a very long time" and probably use AC transmission. The only possible project that could be conceived "within foreseeable future" was transmission of Norwegian hydro power to the European continent. But that possibility was considered too uncertain.[55]

But the Glesum company did not give up their efforts and in late 1933 the company gave a demonstration of their new converter. The result of the demonstration was very positive and ASEA's management discussed if the company should acquire a license to manufacture the new technology but it was decided to wait.[56]

Lamm and his group did not believe in the Glesum system and instead wanted to be able to show to ASEA's management "that there existed a more on principle correct way" to reach the solution.[57] In 1934 the Glesum system would be presented publicly in a presentation at a meeting of the Swedish Association of Electrical Engineers in 1934. When Lamm left his laboratory to attend the meeting a new experimental HVDC MAR was finished but hadn't been tested.

There were great expectations of the Glesum system and ”up to three hundred interested” had come to listen to the presentation.[58] Before the end of the presentation the eager Lamm went away and called his laboratory. He got the message that the MAR ”worked fine” with 25.000 volt which was about 10 times as high as with commercial MARs. Back at the meeting Lamm announced ASEA's MAR solution. When Lamm the next day called the laboratory he was told that he had phoned at the ”right” time the day before since 20 minutes later ”the whole thing collapsed, and after that we never got it going again”.[59]

This basis of this first experimental HVDC MAR – the Ion Valve – was a construction that Lamm had come up with in 1928 when working on improving Schäfer's MAR. When trying to improve the back-fire problem Lamm had come up with an idea on how to solve the problem that he had patented.[60] The new Ion Valve construction stopped operating after a very short time but while it functioned it seemed to show that it was a promising construction.[61]

Lamm's group continued in the following years with several other tests but they all suffered from very severe problems that led to an excessive amount of back-fires.[62] These critical problems together with more urgent issues concerning commercial MARs stopped the HVDC development in the mid-30s.

A Second Try: New Stepped Up Efforts in 1937

In 1937 Lamm's MAR department had time to take up the HVDC development again. The personnel was now less busy with problem-solving in connection with old MAR orders and they ”had gained more experience and training in solving those special kind of issues that fall within that area”.[63] Critical for the further development of low-voltage MARs and high-voltage Ion Valves was a number of problems with materials issues.

In the end of 1937 and beginning of 1938 a series of experiments was conducted on a new Ion Valve construction. The experiments with this construction succeeded in the sense that the ion valve managed to convert up to 35.000 volt DC before breaking down. Nevertheless, the experiments had shown that the modified construction was technically sound and would make HVDC transmission possible.

In 1940 ASEA had come up with a construction that seemed to work longer than a couple of hours and that could be tried in more realistic large-scale tests.[64]

2.4 Shaping the Relations

In this period SSPB and especially ASEA developed both international and national relations that became important in the coming procurement phase. Internationally, ASEA gained an international respect among the international electrotechnical giants. At the same time ASEA and SSPB formed a long-term and intimate relation around developing new technologies together. Both these relations led to ASEA asserting and strengthening its independence and developmental capacity.

2.4.1 Global Institutionalisation: Gaining an International Respect

ASEA had already from its foundation been determined to compete with the major international electrotechnical companies and to be a respected international company. For this it was needed to have a manufacture of all major branches of electrotechnical products. ASEA also went into an European cartel with these companies on a more or less equal basis.

In the 1920s and 1930s ASEA established itself as an major electrotechnical enterprise and managed to keep its independence from foreign companies. In the early 1930s ASEA managed to avoid what seemed to be an attempted take-over by the American giant General Electric.

In the 1930 strategic industrial R&D was institutionalised among international electrotechnical companies. As a part of this institutionalisation ASEA in 1930s followed the other major international companies and changed attitude towards in-house R&D and started to see that as a tool for international competitiveness. That led to the establishment of a high voltage laboratory in the early 1930s and to a new positive attitude towards and willingness to invest in more strategic and long-term R&D such as HVDC.

2.4.2 Local Institutionalisation: Developing a National Trust

The joint HVDC development was not unique but rather a link in a series of previous development collaborations. SSPB and ASEA had together in the 1930s established a Development Pair, an intimate and informal user-producer co-operation around jointly developing new advanced technologies. This joint history of long-term collaborations in uncertain projects on high-risk technologies helped to create in the 40s a relation filled with mutual trust for each partner’s competence and abilities.

The first of these joint projects go back to 1910 when the SSPB engineer Waldemar Borgquist together with ASEA conducted experiments to improve their circuit breakers. Borgquist in 1911 became the chief 'technical manager' of SSPB and these types of experimental development collaborations was taken up again in the 1920s when SSPB's two regional systems in central Sweden were linked by an interconnecting power line of 130.000 volt. This project was the first in Europe to use such a high transmission voltage. Through this it provided incentives to SSPB and ASEA to initiate their first large joint development project, – a project of strategic importance to both partners. ASEA's transformers had not been up to international standard before and this procurement order from SSPB gave the company the chance to catch up. ASEA and SSPB carried out tests together, resulting in the 1930s in high voltage transformers comparable to foreign ones. SSPB's major task from the 1920s was to improve the operational reliability of the power system. One critical problem that was identified was to improve the circuit breakers in the system. SSPB allowed ASEA to use its power plants for experiments on their old breakers as well as try out new constructions. Thanks to this ASEA improved the construction on their old and developed a completely new more efficient breaker.

This collaboration between the state and the private was also characterised by what has been called a ”spirit of national engineers” among Swedish electrical engineers.[65] In the engineering community there were nationalistic sentiments concerning national technological prestige connected to Swedish technology. In Sweden, standing outside the wars the struggle for national eminence came to be fought on the industrial battlefield instead of the military.[66] The historian Jan Glete argues that when discussing SSPB’s close co-operation with ASEA: ”One has to take into account a positive interest in encouraging Swedish industry and Swedish technology”.[67] The ”guarding of the national technology and ambitions to foster it were strong ambitions in Swedish industry” and this ”spirit of national engineers” characterised the electric power sector up to the late 1950s.[68]

3. PROCUREMENT: HVDC in the Making

In this phase the most important version of innovational learning is ”learning-by-interacting” that was so prominent in the collaboration between ASEA and SSPB. It comes mainly in the form of knowledge from large-scale field experiments on prototypes of the technology and from discussions concerning the two parties’ mutual problems.

3.1 Constructing a Problem: Putting HVDC on the Agenda

In 1940 direct current transmissions once again became an issue globally as well as locally in Sweden. The global interest was shown by Soviet plans for building out large waterfalls in Siberia and The Caucasus and transmitting 600.000 kW over 900 km with HVDC.[69] The local interest was shown in a discussion about a Swedish transmission project of less than one-hundredth the size of the Soviet plans. In the summer of 1940 a Swedish HVDC projects was put forward to SSPB. This was in a conversation about Swedish transmission projects between the Director General of SSPB, Waldemar Borgquist and the general manager of SEV, a subsidiary power company of ASEA.

ASEA was not only a manufacturer of equipment for power companies but through SEV it also owned several small and medium-sized Swedish power companies and waterfalls around Sweden. This direct involvement in the power sector made ASEA to a customer and – sometimes – competitor to SSPB. Usually this was not a problem but on this occasion in 1940 it was.

The reason was that ASEA owned the power company on the Swedish island of Gotland and wanted to supply it with power from its waterfall in lower Norrland more than 450 km away on the Swedish mainland. The power should be transferred via SSPB’s existing power lines but since Gotland’s distribution net was isolated from the mainland it would require a undersea power cable to Gotland. SEV’s manager proposed that the power transfer should be with HVDC and using MAR converters. The transfer should be rather small (5.000 kW) and Borgquist found the project interesting but nevertheless objected. This was because if ASEA in the future lacked the power to supply its customers on Gotland, they would surely require to have this power delivered from SSPB and according to Borgquist that would ”surely” come at such a time when ”we have it the hardest.”[70]

This new, more mission-oriented interest in HVDC from ASEA can also be seen through two ’market surveys’ that it did in late 1940. The first was a survey of what had been written previously about possible HVDC projects and through this ASEA got a view of the potential global demand for HVDC. Based on this Lamm did an internal evaluation of the technical and economic reasons for and against using HVDC. His conclusion was that ”there can be no doubt” that HVDC was going to ”obtain a footing” and that it especially was going to be used in Sweden.

Lamm identified two critical problems for a future HVDC successful transmission, where the first were mainly technical and the other mainly of a social nature. The critical technical problem was to develop converters for high voltages and the social critical problem was to establish a development collaboration, ”in collaboration with those power companies concerned try to get a plan for the gradual testing of equipment in a practical scale for larger and larger effects.” To develop this social collaboration ”was as important” as developing the technology since

> ”those on the first hand economically justifiable project are so large, that their realisation must be preceded by the execution of smaller DC-transmissions, which eventually in themselves do not generate any economic profit, but would give experience that are necessary if it will be possible to risk the realisation of the larger projects. […] When one goes about executing projects involving such large investments, one usually avoid large technical risks, in that one seeks to apply constructions and principles that have proven their trustworthiness and operational reliability in smaller projects.”[71]

In 1941 Borgquist and Lamm met and discussed Swedish HVDC projects. Borgquist was himself somewhat of an expert on the issue as, in addition to the Inter-Scandinavian project, he had worked on plans to export power with HVDC from SSPB’s power plant in Trollhättan to Denmark. He also had several practical ideas and suggestions that he wanted to get Lamm’s opinion of. Borgquist proposed that they could use SSPB’s trunk line network to do HVDC experiments ”some weekend”.[72] ASEA had previously in a similar way been allowed to use the trunk line network to test their new construction for circuit breakers.

When discussing a power transmission to Gotland, Lamm made clear that one always had ”to count with some risks”. But despite this Borgquist was very optimistic and saw it as possible to have a transmission ready the summer of 1943 and if the Swedish cable manufacturers – to which a ASEA subsidiary belonged –

would ”be willing to manufacture and put out the cable without any profit mark-up” it could be possible to seriously consider an ”immediate cable purchase”.[73]

But despite SSPB’s optimism it did not become any ’immediate purchase’ and HVDC instead became considered for a much larger transmission project, a Swedish super power project.

3.2 Entering Procurement: Formalised Joint Problem-Solving

In the spring of 1942 SSPB started the preparations for a future super power transmission from Norrland. In central Sweden 20 % of the exploitable hydro power remained and was rather expensive to build out while in lower and upper Norrland around 70 and 90% was still unused.[74] To prevent the number of large transmission power lines from Norrland from becoming too many it became necessary to develop a technology with higher transmission capacity than before.

As previously mentioned, the state inquiry in 1936 had said that the future power system should be built out in collaboration between SSPB and the major private and municipal power companies. The suggestion was to form a joint committee that should investigate the problems in connection with the coming exploitation of Norrland in the mid-50s. Its main task was to investigate the possibilities to use AC transmission with much higher voltages than before or to use HVDC transmission. This was a much larger project than previously discussed and Borgquist was this time less optimistic of HVDC and was ”doubtful concerning the assurances that is made about its usefulness”. Nevertheless, he found it ”very laudable” that ASEA had started developing HVDC converters, even if he considered it ”doubtful whether ASEA with their limited resources will be able to solve a problem where the major international firms have not succeeded.”[75]

The first meeting with the Swedish Collaborative Committee for Superpower Transmissions was held in June 1942.[76] The Committee consisted of representatives of SSPB and the three other Swedish utilities that owned power lines of 220.000 volt together with the potential Swedish manufacturers that was ASEA and a cable company.[77]

ASEA had started experiments with a new improved Ion Valve and the day after this first meeting with ASEA SSPB started to investigate if it would be possible to use one of their power lines for the large scale and long-term testing that ASEA wanted to do on their new construction.[78]

The difficult problem of developing Ion Valves was that they couldn't be constructed according to known laws of electromagnetism and theoretical formulas but had to use knowledge from empirical trial-and-error work. This had to be done in full scale experiments with almost operational voltages, which demanded large amounts of electric power. Furthermore, it was needed to test modifications of the construction during a very long period of operation because of the possible critical problems of ageing of the material inside the valves and the random and unpredictable character of the back-fires. All this meant that the development was very time consuming, expensive and demanded large amounts of power.[79]

The new collaborative committee conducted an investigation about AC versus DC that confirmed that HVDC would give lower transmission cost than AC.[80] The cost with DC was estimated as 2/3 the cost with AC.[81] Following this ASEA and SSPB decided to go ahead with a more formalised co-operation.

3.2.1 A Contract to Procure Joint Experience

In December 1943 ASEA and SSPB signed a agreement to ”jointly establish and operate an [experimental] power transmission for HVDC”.[82] The transmission was going to be operated during a long enough time to give ”most complete experience basis for the consideration of a possible use of HVDC for future super power transmissions from Norrland to central Sweden.”

This experimental transmission set-up would consist of a power line connecting two converter stations. One station was to be built in the switchyard belonging to SSPB's hydro power plant in Trollhättan and the other in one of its small substations 50 km away, in Mellerud. Except for supplying the power to the transmission experiments and building the experimental converter stations SSPB should supply the personnel operating the power line. ASEA was supplying the Ion Valves and the equipment used in the experiments. Furthermore it should also provide the necessary personnel and equipment for the different experiments. All other expenses should be divided equally between the two parties. According to the contract the results from the experiments should be freely available to both parties although they could not be communicated to outside parties without the other's approval.[83] The transmission was estimated to cost 1,3 million Crowns to build and the experiments was planned to commence during the end of 1944 and be finished at the beginning of 1948.[84]

While waiting for the experimental transmission link to be erected the experiments at ASEA continued and in 1943 ASEA performed the first successful long-term experiments on a Ion Valve construction. The following year the experiments had been expanded to a full transmission set-up of two Ion Valves where the first were used to convert AC to DC which the other converter changed back to AC again.[85]

But an important test still lacking was to actually transmit power over longer distances and to try out how the converters worked in the field rather than in the laboratory.

3.2.2 Confronting Critical Technical Problems

A possible economic salient of using HVDC would be if it would be possible to solve the critical problem of using ’earth-return’ for the transmission. This meant that the earth (or the sea in case of a undersea transmission) between the two converter stations were used as a conductor for leading back the returning DC current. This would mean that only one power line was needed instead of two without the earth-return or three with AC. Since a large cost of the transmission set-up usually consisted of the cost for lines or cables this would mean very large savings for DC compared to AC.

However, an important critical problem of using earth-return was that it could cause damage and disturbances to other large and widespread technical systems such as telephone cables or the railway networks. To investigate if this was the case SSPB and ASEA in 1944 started a series of large-scale experiments in collaboration with the Swedish Telecommunication Administration (STA), the State Railways and Chalmers Institute of Technology.

First earth-return was investigated in a 50 km transmission of low-voltage DC between Trollhättan and Mellerud. After this the size of the experiment gradually increased until almost spanning the whole length of the country.

The Country as a Learning Laboratory

These experiments continued with even more large-scale field experiments where almost the whole country was made to adapt to the experiments and used as a ’table-top’ for the experimental set-up.

The first of these were conducted during a Saturday night in November when DC was transmitted 315 km via one of SSPB’s long power lines. The experiment was to investigate the effect of earth-return conduction on the signal system of the railways and on disturbances on underground telephone cables. During the five minutes the experiment lasted all trains in central Sweden were stopped because of the danger of faulty signalling that could be created by the DC transmission. The experiments also showed that a real super power transmission using earth-return would give a serious risk of wrong signals within 150 km from each electrode. The critical problem still remained unsolved.

During the summer of 1945 this ’macro-experimentation’ continued with what was said to have been ”one of the most exceptional electrotechnical experiments performed in recent time”[86] This was a DC transmission 300 km between Haparanda and Umeå but this time using the Baltic Sea as a return conductor. This was a continuation of a previous experiment of transmitting power 460 km from a fjord outside of Gothenburg to a coastal town that had failed because the current had been too weak. By using sea-return one hoped to avoid disturbing the telephone and railway systems on the mainland.[87] This experiment succeeded in the sense that this seemed to be the case for the major part of the current.

The Switchyard as a Learning Laboratory

Meanwhile, the completion of the experimental stations in Trollhättan and Mellerud had been delayed with a year because of a nation-wide strike at the end of the war. The transmission set-up was finished in October 1945 but then also the preconditions for the transfer had changed because of the earth-return problem.

The ’earth-return’ problem had changed from being a possible salient to becoming an actual reverse salient for the HVDC experiments. This was because when it was shown that it disturbed the other large technical systems, the large risk of disturbing the railways between Mellerud and Trollhättan and of damaging the telephone cables made it not possible to conduct any long-term transmission tests. What could be done however was to simulate such a power transfer inside the switchyard in the Trollhättan power station with an AC/DC-converter connected over a large resistance (’the power line’) to a DC/AC-converter.

The most important part of the testing was the experimental testing of the Ion Valves which now could be moved from ASEA’s laboratory to Trollhättan. These empirical testing was done through life-time experiments where teams of ASEA’s specialists together with SSPB’s operators worked around the clock in Trollhättan for several months of time. Lamm has given a vivid description of the reasons for this long and arduous engineering work.

> ”[ASEA] have tested [...] different modifications of the interior design of the valves, many of them in two or more samples. The more fruitful modifications have been run for a period of about half a year, or longer, while quite a number have been run unchanged for several years. One would like,

> of course, to finish the test on one modification before one goes on with the design of the next, but as the time that elapses between building a new modification from the first sketches and obtaining the first test results can generally not be cut down below 9 months, it is quite obvious that one must work with a great number of modifications ’in parallel’. The setting out of a design, therefore, often has to include a lot of guesswork regarding the outcome of previous designs which are still under construction in the works”.[88]

The rest of ASEA’s HVDC development work could be divided in the two main tasks of designing the converter station’s regulation and control system, and scientific research on gas discharge physics.

The work of designing the regulation system was possible to do based on exact mathematical calculations or through simulations on an electrical network model of the future transmission link.[89] The last part of the development work was conducted by a group of physicists at ASEA’s plant. They tried to come up with theoretical explanations to the different observations in the trial experiments in Trollhättan. They also conducted different experiments in which they tried to study the different physical phenomena that took place inside the ion valves. This was to try to ”get larger possibilities to through pre-calculations replace some of the arduous empirical development work”[90]

3.2.3 Solving an Institutional Reverse Salient

Another reverse salient for future super power transmissions in Sweden was of an institutional nature. That concerned the ownership and operation of the future super power lines. Except for the state, also private companies owned hydro power in Norrland. It would not be practically and economically justifiable that every one that owned power in Norrland and wanted to transfer it south should build its own power transmission line. Therefore they must have to transfer it on power line owned by other companies. Since it was decided that the future power system was going to be build out in cooperation between private and public utilities it was predicted that several critical problems would arise concerning ownership of the power transmitted etc.

SSPB in early 1945 proposed a solution that would eliminate this reverse salient. SSPB proposed to the three other main power companies who owned power in Norrland, that the four of them should form a joint company that should take over all old large power lines and build all new super power transmission lines.[91] None of the other companies were really interested in the proposal but after hard negotiations SSPB managed to get them to agree on the proposed company. This company should ”own, build and operate” all future large transmission lines."[92]

During the spring of 1945 SSPB asked the Government to approve the proposed joint company. However, it was different views among the parties of the ruling coalition government and no decision was taken until the change of Government following the end of WWII. In November the new Social Democrat government decided that the State – i.e. SSPB – should own and be responsible for any new Swedish super power transmission lines. This meant that it became the sole responsibility of SSPB to decide what technology to use for future super power transmissions.

3.2.4 Increasing Demand and De-Selecting Supply

In 1946 the HVDC experiments in Trollhättan continued with some real transmissions of 2.000 kW to the station in Mellerud. This was to investigate any eventual disturbances on the line coming from other components in the power grid. After this the experiments continued again in the station in Trollhättan. Furthermore, SSPB performed a series of experiments together with the STA on the effect of DC and AC on radio disturbances and energy losses from the power lines.

In September 1946 yet another large-scale experiment was performed with earth-return. This was a full-scale experiment in its true sense since it was a transmission of 1.000 km. The north electrode of the transmission line was placed in a mine in upper Norrland and the south in a fjord outside Gothenburg. But the experiment gave rather few positive results and strengthened the negative ones from previous experiments that showed that HVDC super power transmission with earth-return could seriously disturb the railway and telephone systems.[93]

During the autumn of 1946 the plans for building out the waterfall at Harsprånget were suddenly brought forward. The anticipated post-war depression did not come and instead there was an increase in the demand for electric power. Therefore it was seen as necessary to start building out the hydro power in upper Norrland earlier than foreseen. SSPB had to take their decision about what technology to use for the super power transmission already during 1946. Both AC transmissions over 300.000 volt and HVDC was very unsafe choices. HVDC did not exist and the world record voltage used for AC was 287.000 volt.

ASEA did not dare to take the risk with the untried HVDC system. Lamm said that judging from previous and present problems "that there are *no* chances to get the

DC system fully ready and enough tested in time for the first stage of the exploitation of Harsprånget, while the prospects look good to have it ready in time for it to be applied to the major part of the [other] build-outs in upper Norrland."[94]

In December 1946 SSPB decided to use AC technology for the build-out of Harsprånget. SSPB entered in a GTP project with ASEA around developing a 380.000 volt AC technology. The project was successful and the first power line from upper Norrland was inaugurated in 1952. But this had not meant the end for HVDC.

3.8 Reconstructing Procurement: Return of an Old Project

The Power Board and ASEA in 1947 decided to continue their HVDC collaboration with the aim of developing Ion Valves that were to be used for future Swedish super power transmissions of 100.000 kW.[95]

It soon obvious that the old experimental converter station in Trollhättan would not be large enough for these experiments and in 1948 it was decided to build another larger joint laboratory next to the old one. The new laboratory would make possible experiments on ion valves up to 25.000 kW instead of the 3.000 kW that was maximum of the old laboratory.[96]

At the same time an old HVDC project had been taken up again in 1947 when, barely a month after the Harsprånget-decision, the question was anew raised in the Parliament to have an inquiry about the possibility to supply Gotland with electric power from the mainland.

Gotland had a special status in Sweden as being the only part of the country without hydro power or connection to the national grid. Because of this ’power isolation’ and the high fuel costs the electricity prices on Gotland during WWII had been much higher than in the rest of Sweden. The government approved the inquiry and in March 1947 ordered SSPB to investigate the possibility of supplying Gotland with electric power. SSPB gave the assignment to one of its engineers together with an engineer of the ASEA company that owned the power plant on Gotland.

A power transmission to Gotland would be a very suitable first project for ASEA then it would be of a ’lagom’ – Swedish for not too much, not too little – size and difficulty. This was because the amount of power that was going to be transmitted was only 20.000 kW compared to 150-400.000 kW for a super power transmission. Furthermore there was no risk of any conflict with competing or dissatisfied power producers since ASEA owned the only power producer on Gotland. This also meant that there was less risk of any heavy claims for damages if the project failed.

As had been the case for the planned super power transmission, an important condition was that the HVDC transmission did not disturb or damage surrounding large technical systems. The inquiry with the help of Chalmers Institute of Technology investigated the disturbances to the telephone cables to Gotland and found that disturbances could easily be avoided.[97] A further condition was that the transmission did not damage sea life because ”possible demands from the fishing industry might bring to nothing the economic gain of using one instead of two cables”[98] In the summer of 1949 SSPB together with the Board of Fishery conducted model experiments to investigate the effect of DC on the flora and fauna of the sea. In these experiments a model transmission link of 1 km and 200 A with sea-return was used. The results showed that any problems could easily be avoided by shielding the electrodes from the fish.

The joint inquiry by ASEA and SSPB was finished in January 1949. The inquiry had found that AC was not economically justifiable because of the long transmission in cable that created large losses that not occur in DC cables and therefore recommended HVDC transmission. Concerning the advantages of this it stated the primary advantage to be lower electricity prices on Gotland, and furthermore it said that the creation ”of an operational [transmission] for reasonable effect will be positive also for the work on larger [transmissions], that will be needed for long distance transmission for large effects”.[99] The inquiry proposed that the transmission should be built out in three stages. The first stage of 10.000 kW should use one cable for and one converter unit with sea-return. In the second phase the effect should be increased to 20.000 kW by adding one extra converter group in series with the first. In the third and last phase the effect should be raised to 40.000 kW by replacing the sea-return with a second cable.

In 1949 SSPB followed the recommendations from the inquiry and presented the government with a proposal to build an power transmission to Gotland using HVDC. The government followed the proposal and put forward a government bill that was accepted by the Riksdag and in 1950 the procurement contract between ASEA and SSPB for the Gotland transmission could be signed.[100] A major change was that after discussions between ASEA and SSPB it had been decided to go for a transmission of 20.000 kW and not 10.000 kW as first suggested. According to Lamm the technology was not considered as safe since it was still under development and all involved knew that the project meant ”considerable technical risks”.[101]

The new ion valve laboratory in Trollhättan was finished during the autumn 1951 and all experiments was now totally focused on developing the Ion Valves that were to be used in the Gotland transmission. The two converter stations should each have two converter groups of 10.000 kW each. Every group consisted of six ion valves and a ’by-pass Ion Valve’. This by-pass valve was Lamm’s second solution to the problem of back fires. It had been possible to decrease but not to completely eliminate the back-fires altogether. Since it had been impossible to completely eliminate them even in commercial low-voltage MARs the group had found it as ”sound realpolitik” to accept them and instead ’invent around’ the problem.[102] This was done by using a method that was used in commercial MARs. This was to automatically block all the converters ion valves when a back-fire occurred and then let the current pass through a by-pass valve. And when the back-fire had disappeared the current came back as normal.[103]

After the decision one and a half years were spent on further development of the ion valves. This time was used to test different modifications. When the decision about the final construction was taken in 1953, around 140 different Ion Valve constructions had been tried and several in two or more versions.

3.9 Supplying the Product: Laying the Link

The set up of the Gotland transmission began in 1952. The whole transmission consisted of two converter stations and one underwater cable. In the mainland converter station power was taken from the national grid and converted to DC of 100.000 volt and then transmitted through the cable to the converter station on Gotland. Here the power was converted back to AC before it was sent out to consumers on Gotland. The transmission used only one cable and the circuit was closed by sea-return. The station buildings were also built so that it would be possible to increase the effect to 40.000 kW at a later stage by doubling the number of converters and by laying an extra cable.

The 96 km long cable was put out in June 1953 and the first part of the transmission started in March 1954. At this time only one converter for 10.000 kW had been delivered to each station and during the first period only small amounts of power was transferred in the cable. During the trial transmission that followed it was possible to tune in the details of the equipment and to do ”some measurements under realistic conditions and from this construct, manufacture and assemble some supplementary details”.[104] The remaining part of the equipment was delivered at the end of July 1954 and the transmission voltage was raised to 100.000 volt and from the end of November the HVDC link supplied all of Gotland’s electric power.

According to the contract the try-out transmission should continue until 1957. However, since SSPB was so satisfied with the trial results it was decided to bring forward the take-over by SSPB by a year and January 1st 1956 the transmission was taken into commercial operation by SSPB.

The whole transmission had originally been estimated to cost 9,5 million Crowns but had because of an additional build-out of the plant increased to 19 million Crowns.[105] This was however a low price for SSPB that got the equipment to the same price as ASEA’s manufacturing cost.[106] The price of 19 millions can also be compared to a SSPB assessment from 1959 that estimated that SSPB’s total costs for the HVDC development work in Trollhättan until 1954 was 2.6 million Crowns.[107] The cheaper hydro power of SSPB that was transferred through the new transmission link lowered the prices of power on Gotland to half of what they had been before the link.

Furthermore, ASEA also gave up the right to control the operations of the Gotland steam plant to SSPB.[108] A ’lagom’ large cost for the opportunity to develop a ’lagom’ small first commercial transmission.

4. POST-PROCUREMENT: Re-Shaping Power and Products

4.1 From DGP to AGP: HVDC in the Re-Making

In 1957 the governmental English and French power companies British Electricity Authority (BEA) and Electricité de France (EdF) placed an order to ASEA of ion valves for a HVDC transmission under the English Channel. This transmission was on 160.000 kW, eight times the amount of power transmitted in the Gotland project. The total cost for the project was 70 million Crowns with ASEA's share of 16 million Crowns.[109]

Although the formal procurement process began in 1957 this GTP – that was of an AGP kind – had also its proto-procurement phase. It started in 1950 when a joint French-English committee was appointed to investigate the possibility of an power exchange between the two countries. This promised to be very beneficial because the two electric power systems complemented each other in a very good way and estimates had shown that such a power exchange could save building power plants for additional 300.000 kW in the two countries.[110]

The distance over the Channel was rather short, 40 km, which meant both AC and DC was possible. The committee presented its official report only three weeks after the Gotland transmission had started trial transmission and the report proposed using AC.[111] Concerning HVDC it stated that much ”effort and money” had been devoted to it but that ”so far no tangible success has been commercially demonstrated” and because of the ”immature state of development” a DC interconnection ”was not immediately practicable”.[112] It nevertheless stated that an experimental DC transmission under the Channel ”merited serious consideration.”

When the report was due to be publicly presented in April 1954 to the Institution of Electrical Engineers in London, Uno Lamm travelled there together with SSPB's director general and vice director general. During the meeting the Swedes informed about the Gotland transmission and showed pictures from its opening. And despite the report in the summer 1954 that the technical preconditions were settled in favour of AC, ASEA with the help from SSPB was lobbying heavily to convince the French and English engineers about the advantages of HVDC and above all about its trustworthiness.[113]

The committee had from the beginning in mind an AC transmission with four cables where the fourth cable was a spare cable. The idea was to also use this cable to experiment on a HVDC transmission in parallel with the normal AC power transfer. If that worked well, a changeover would be done from AC to DC at a later However, such a solution could not be accepted by the British Admiralty. This was because if the sea was used as a return conductor it would create a small error in compass inclination in the very heavy trafficked English channel. Despite the fact that the error was considered insignificant, EdF and BEA thought that it ”would take 10 years to convince the Admiralty” about that.[114] Therefore it was necessary with two cables for HVDC already from the beginning, which meant it was impossible with a gradual changeover from AC to DC. The issue whether DC or AC ”had consequently to be decided from start”.[115] DC had several large advantages such as that the expected economic savings with DC was around 4 million Crowns compared to 1,3 millions with AC.[116] Furthermore, the DC system promised to be more reliable with only two cables instead of four with AC.

In 1954 and 1955 the discussions continued between ASEA and the engineers of the two power companies. After a while ASEA’s engineers were allowed to ’informally’ participate in the meetings with the joint committee. And after a while these meetings turned into serious negotiations until 1957 when the power companies placed their orders to ASEA. The transmission had now been changed to a DC cable of 64 km and with ion valves of twice the current and voltage as compared to the Gotland transmission, and with eight times the effect.

This was also a GTP project of the Adaptive GP version. The collective procurers were the government agencies BEA and EdF. The major adaptive innovation activities concerned the further development of the Ion Valves and the regulation system of the link. The new larger Ion Valves were based on the knowledge gained from the Gotland transmission and had twice the voltage and current of those at Gotland. ASEA finished their construction of the new Ion Valves in January 1959.

The other major novelty compared to the Gotland link was the technology for the regulation of the exchange of power between the two cable stations. In the Gotland transmission this had been done manually with telephone contact between the two stations. In the Channel project this was done by an automatic control system. The reason for this was the different languages and operational routines that was used in the two different organisations (EdF and BEA) that shared the cable and the two stations.[117] The difference in the two cultures that had been an advantage to the power exchange, here became a disadvantage.

The transmission of 160.000 kW was taken into operation in December 1961. The HVDC technology had matured and taken its first steps out on the European and international market.

4.2 Pros of the Producer: Competitive Products for ASEA

The Channel project had been the first export project in where ASEA managed to sell its new product – the HVDC transmission technology. This project was followed by other successful international projects in the 1960s. This was foremost like the Channel project for long underwater transmissions of 200.000, 250.000 and 600.000 kW in Italy, Sweden-Denmark (Konti-Skan, see below) and New Zealand.

But the HVDC technology also found other areas of application. The first was when ASEA in 1965 inaugurated a converter station of 300.000 kW in Japan. Here HVDC was used not for transmitting power long distances but as a tool for integrating two neighbouring AC-distribution systems with very different electrical characteristics. This was done by using the HVDC technology as a ’gateway technology’ to convert AC-electricity of one system standard (50 Hz frequency) to AC of the other system’s standard (60 Hz) and vice versa.

Furthermore HVDC also found use in its originally intended use in the Swedish development project – as an overland transmission link for super power transmission. This was when ASEA in collaboration with GE in 1965 got a joint order for the so called Pacific Intertie. This was a more than 1.300 km long HVDC transmission of 1.440.000 kW from the Colorado River in Oregon to Los Angeles in California. This was also the first project where HVDC had competed equally with AC. Thanks to this HVDC had proven its superiority over AC for long super power transmissions. Also this was a GTP project then the major buyer was two federal and municipal power companies. Like the Channel project this was also of a AGP type of GTP, although with Ion Valve converters that had been developed to more than 15 times the effect of those at Gotland.[118]

Up until the 1970s ASEA had a practical monopoly on HVDC technology world-wide with a profit margin of 20 %. In the 1970s the HVDC Ion Valve converter technology met harsh competition from new HVDC Semiconductor Thyristor converters. ASEA switched to the new technology and thanks to its experience in the Ion Valve technology managed to keep its leading position. The economic result of ASEA’s HVDC Ion Valve technology was orders on 545 million crowns in 1954-73 with net profits of around 74 million crowns which was 13,5 % of the HVDC turnover.[119]

Up until 1951 ASEA had spent 5 million crowns on the HVDC development work to be compared with the around 2.2 million crowns spent by SSPB. In 1960 ASEA had spent around 22 million crowns to be compared to around 6.4 million crowns by SSPB. But SSPB profited from its investments in its next large super power transmission project that it started in 1960.

4.3 Pros of the Procurer: Competitive Power for SSPB

The HVDC was never used by the SSPB for its intended use, to transmit power from Norrland to Southern Sweden. The further transmissions in the 1950s and 1960s that was envisaged to use DC instead used the existing AC technology. Instead the HVDC came to be used in another large power project when SSPB redefined its demand from local Swedish to European in the 1960s.

This was a project of European integration in a very practical sense by building a power link between the Scandinavian peninsula and the European continent. Because of the great build-out of hydro power in upper Norrland there was a large surplus of power in SSPB's system that during could be used for a ”profitable export” to West Germany.[120] In the early 1960s discussions started concerning an exchange of power between SSPB's power plants and those in Denmark and West Germany which would mean great economic savings because of the complementary diversity of different national consumer patterns and national energy resources (hydro power vs. steam power).

A joint committee of the involved power companies came to the conclusion that HVDC was the most suitable technology for this so called Konti-Skan link. The super power transmission was for 250.000 kW and the whole project cost around 100 million crowns and in 1963 SSPB ordered equipment of 50 millions worth (equals around 400 million crowns 1997) from ASEA.[121] The Konti-Skan project was seen as meaning cost reductions and profits of the same order of magnitude through reduction of the needs of thermal power in Sweden and export of surplus power.[122] This cost can be compared with the sum of 6,4 million crowns which was the estimate of SSPB's cost until 1960 for the joint HVDC development work in Trollhättan.[123]

The project was described as ”the European highway of electric power” and as opening the gate for ”a complete European exchange of power”.[124] The Konti-Scan project was successfully inaugurated in 1965.

5. CONCLUSIONS: Shaping Tools for History and Policy

5.1 Lessons for History: De-Constructing Linearity

This case study has shown how GTP was used for introducing a new innovation to the market by bringing proto-supply and proto-demand together in a first commercial project. After this first small project the scale of the following projects as well as the capacity of the technology improved gradually. The technology was then subsequently used as a tool for increasing the international competitiveness of the procurer as well as the producer.

In several retrospective descriptions this development has been described as a straightforward linear process following a pre-planned route in more or less the following order: // goal / invention / development / goal-sharpening / prototype / trials / procurement / development / innovation / transfer //. But as has been shown this was not the case, but rather the process seemed very open and uncertain to the involved actors. The direction of the development was redirected because of a web of social, technical, political and other factors which reshaped the demand the technology should fulfil as well as the 'supply' – the HVDC technology. A route closer to the events described is: // invention / development / failure / project-restart / development / prototype / goal(1) / goal(2) / trials / goal(1) / procurement / goal(3) / development / innovation / development / transfer //.

The above sequence also looks different from the procurer's perspective. This is especially clear if we look how at the procurer's specific demand that the HVDC was going to fulfil was redefined over time. From SSPB's perspective HVDC was in the proto-procurement phase seen as a tool for exporting surplus power (The Trollhättan-Copenhagen project) and then changed to a tool for helping a neighbour country in crisis (The Inter-Scandinavian project). In the procurement phase it was first seen more of a problem in that it could create unwanted demands from no-customers (the first Gotland project plans), and then changed to make possible the exploitation of a new large source of power (The Norrland project) to being a tool for lowering the energy price in an isolated region (The Gotland project). After that in the post-procurement phase it was again changed into a tool for a profitable export to the European continent (Konti-Skan). So if one would have asked what was the purpose of developing the HVDC technology, there would have been different answers depending on when the question was put.

It has shown that in GTP as in other innovation processes, social problems and possibilities are as critical in shaping the outcome of the procurement process as the technical problems and possibilities – it is a sociotechnical process where the technical and social factors are integrated. This of course creates some repercussions for procurement policy.

5.2 Lessons for Policy: Develop Sociotechnical Links

What this case study has shown is that procurement is a complex and changing process, where the social and technical are always interconnected in a changing process. One of the most important roles for policy makers who want to create conditions for successful procurement projects could be to create conditions for developing and strengthening such important sociotechnical links.

Create 'Arenas for Sociotechnical Learning'

Crucial for the successful outcome of the HVDC procurement project was that before the actual procurement project (and during) there was a long period of 'sociotechnical learning' through broad and exploratory problem-solving. This was accomplished through the use of old or creation of new sociotechnical arenas (meetings of the Assoc. of Electrical engineers, joint committees, joint laboratories etc.) that acted as fora where several of the major parties involved or affected by the project-to-be could meet and learn from each other's diverse knowledge regarding the different actual and potential critical sociotechnical problems (finding a reference project, comparing AC vs. DC, exploring earth-return etc.). Important to notice is that this learning was something that went on for a long period before the actual procurement projects were initiated. An important role for future procurement projects could be to *long in advance of deciding about a project* create such arenas and initiate such exploratory problem-solving discussions regarding sociotechnical problems between major potential parties and interest groups. And for large European projects of course these arenas have to be organized on a European rather than national level.

Look for 'Sunken History'

The procurement was supposed to create something very 'new' but did this by utilizing 'old' resources and relations. When the GTP project started it very much profited from a 'sunken history' in the form established technical and social investments that had been developed during a long period of time. Some of the most important such resources was: the *producer's absorptive capacity* in a field of commercial and proven technology (MARs) that could be utilized in the new exploratory field; the *user's familiarity of the demands* that the new innovation had to satisfy and that could be used to foresee future problems; the *procurement partners's mutual social trust* that had been developed through previous joint projects and could be used in overcoming mutual problems and maintaining confidence in the positive outcome. When developing something new, don't be too new but build on old proven resources.

5.3 Links to other ISE projects

Except for those other projects looking at government technology procurement in sub project *3.2.2 Government Technology Procurement as a Policy instrument*, there are also links to other sub projects in ISE.

The general theoretical perspective used in this case study utilize and extend those systems and evolutionary approaches treated in *3.1.1 Systems Theories of Innovation: Policy Implications*, Especially as in *3.1.3 European Integration and National Systems*, the role of diversity in supply and demand and learning is emphasized.

The Development Pair between ASEA and SSPB is a ”corporate governance mechanism” that was very positive for innovation performance and organizational learning as discussed in *3.2.4 Corporate Governance and Innovation Performance*.

The HVDC case is also an example of a ”technological entry” process – if not sectoral entry – where, as discussed in *3.2.5 Technological Diversification vs. new Innovators*, a large company enters a new technology twice (MARs and HVDC). Since it is a rather detailed case study it gives a good example of how a large firm has handled the diversification process.

When it comes to special relations between different elements in NSIs, the case of the HVDC has treated the effectiveness of user-producer interaction. In this the government user provided support to the innovation activities through technical and financial risk-sharing and technical advice. These innovational dynamics is interesting to compare to the results of *3.2.3 Financing of Innovation* which analyze the innovational dynamics of borrower-lender interactions and government support via funding and economic risk-sharing. It might be possible to say something about the relative importance to industrial companies of financial resources and economic know-how vs. technical resources and technological know-how.

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Sylwan, Einar, ”Storkraftöverföring: Svensk försöksanläggning för kraftöverföring med högspänd likström”, *ERA* 17 (1944), 55–7.

Uhlmann, Erich & Engström, Gunnar, ”Kraftöverföring med högspänd likström över Engelska Kanalen”, *ERA* 31 (1958), 31–2.

von Hippel, Eric, *The Sources of Innovation* (Oxford, 1988).

Wollard, Katherine, ”Uno Lamm: inventor and activist”, *IEEE Spectrum* 25 (March 1988), 42–45.

Notes

[1]The following discussion of GTP is based on the results from an email discussion with the members of the ISE GTP sub-project.

[2]Mats Fridlund, "Ett svenskt utvecklingspar i elkraft: Aseas och Vattenfalls FoU-samarbete, 1910–1980", BI Forskningssenteret forskningsrapport 1995/2 & Senter for elektrisitetsstudier 1995/312/7 (Sandvika: Handelshøyskolen BI, 1995), 1-2. – I have previously used a somewhat broader definition, see: Mats Fridlund, ”The ’Development Pair’ as a Link between Systems Growth and Industrial Innovation: Cooperation between the Swedish State Power Board and the ASEA Company”, Working papers from the Department of History of Science and Technology 93/9 (Stockholm, 1993), 4.

[3] See for instance: Jan Glete, *Storföretag i starkström: Ett svenskt industriföretags omvärldsrelationer - en sammanfattning baserad på "ASEA under hundra år"* (Västerås, 1984); idem, "High Technology and Industrial Networks: Some Notes on the Cooperation between Swedish High Technology Industries and their Customers", (Paper presented at ”International Research Seminar on Industrial Marketing” at Stockholm School of Economics, Stockholm, August 29-31 1984); *Framgångsrik utveckling av energiteknik*, IVA-M 278 (Stockholm, 1992), 6; Charles Edquist & Bengt-Åke Lundvall, ”Comparing the Danish and Swedish Systems of Innovation”, in: Richard R. Nelson, ed., *National Innovation Systems: A Comparative Analysis* (NY: Oxford University Press, 1993), 281.

[4]Eric von Hippel, *The Sources of Innovation* (Oxford, 1988).

[5]The complete term is ’capitalist developmental state’, but developmental state is the common term used. Chalmers Johnson, *MITI and the Japanese Miracle: The Growth of Industrial Policy, 1925-1975* (Stanford, 1982), passim, spec. 17-34, 305-324. Also see, Chalmers Johnson, *Japan: Who Governs? : The Rise of the Developmental State* (New York & London, 1995), esp. ”Introduction” & chpt. 2, 5, 6, 7. Cf.: Stephen S. Cohen & John Zysman, *Manufacturing Matters: The Myth of the Post-Industrial Economy* (New York: Basic Books, 1987), 249-53.

[6]Based on: Johnson 1982, 315-320.

[7]Peter Evans, *Embedded Autonomy: States and Industrial Transformation* (Princeton, 1995), 12.

[8]The term of the ”shaping” of new knowledge is from: Martin J.S. Rudwick, *The Great Devonian Controversy: The Shaping of Scientific Knowledge among Gentlemanly Specialists* (Chicago, 1985), xxii, xxi.

[9]The method of studying innovations ”in the making” is mainly taken from the perspectives of Bruno Latour, Martin Rudwick and Göran B. Nilsson: Bruno Latour, *Science in Action: How to Follow Scientist and Engineers through Society* (Milton Keynes, 1987), passim; Rudwick, *The Great Devonian Controversy*, 11-14; Göran B. Nilsson, ”Historia som humaniora”, in: idem, *Den lycklige humanisten: Tio offensiva essäer* (Stockholm, 1990), 50-54.

[10]Rudwick, 12.

[11]I use the term ”problem construction” instead of the more common ”problem formulating” to emphasise that the problems that should be solved are not clear but that they like the technological solutions must be constructed and are open to re-construction.

[12]For description of Hughes’s technological systems and reverse salients, see: Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore, 1983), 66, 79; idem, "The Evolution

of Large Technological Systems", in: Wiebe E. Bijker, Thomas P. Hughes & Trevor Pinch, eds., *The Sociological Construction of Technological Systems: New Directions in the Sociology and History of Technology* (London, 1987), 51-83; idem, ”The Dynamics of Technological Change: Salients, Critical Problems, and Industrial Revolutions”, in: Giovanni Dosi, Renato Giannetti, & Pier Angelo Toninelli, eds., *Technology and Enterprise in a Historical Perspective* (Oxford, 1992), 97-118.

[13]Salients and reverse salients are very similar to what economic historian has called ’structural tensions’ in development blocks, see: Erik Dahmén," ’Development Blocks’ in Industrial Economics" (1989), in: Bo Carlsson & Rolf G. Henriksson, eds., *Development Blocks and Industrial Transformation: The Dahménian Approach to Economic Development* (Stockholm: Industrial Institute for Economic and Social Research IUI, 1991), **xx-yy**; idem, ”Schumpeterian Dynamics: Some Methodological Notes” (1986), in: Bo Carlsson & Rolf G. Henriksson, eds., *Development Blocks and Industrial Transformation: The Dahménian Approach to Economic Development* (Stockholm: Industrial Institute for Economic and Social Research IUI, 1991), 126-35. For the similarities between Dahmén’s and Hughes’s technological systems, see: Carlsson, Bo & Pontus Braunerhjelm, *Teknologiska system och ekonomisk tillväxt: En studie av de mikroekonomiska mekanismerna för tillväxt*, Bilaga 10 till Långtidsutredningen 1994 (Stockholm: Finansdepartementet, 1994), 9-10; Carlsson, Bo, Eliasson, Gunnar, Granberg, Anders, Jacobsson, Staffan, & Stankiewicz, Rikard, *Sveriges teknologiska system och framtida konkurrensförmåga: Preliminär rapport från STS-projektet*, R 1992:65 (Stockholm: NUTEK, 1992), **xx-yy**; Mats Fridlund, ”Schumpeters tvillingar: Utvecklingsblock och teknologiska system i industriell utveckling”, in: *Perspektiv på industriell utveckling*, Staffan Laestadius & Jan Odhnoff, eds. (Stockholm: KTH, forthcoming), passim.

[14]The term ’system builder’ is here used to denote those actors that are actively and consciously involved in activities that aims at developing technological systems. Consumers and labourers are not considered system builders.

[15]For a discussion of the social character of ”technological salients”, see: Donald MacKenzie, "Missile Accuracy: A Case Study in the Social Processes of Technological Change", in: Bijker, Hughes & Pinch, 196-8; idem, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, 1990), 79-80. – An example of a re-construction of system goal could be when the ’efficiency’ of energy systems are changed from being measured primarily in purely economic terms but also including environmental terms, leading to new components being identified as salients and reverse salients and the redefinition of other old components previously being considered highly efficient and of a salient character to now be of a reverse salient character (like a nuclear plant).

[16]Nathan Rosenberg, ”Learning by Using”, in: idem, *Inside the Black Box: Technology and Economics* (Cambridge, 1982), 120-40. Also cf.: Staffan Laestadius, *Technology Level, Knowledge Formation, and Industrial Competence within Paper Manufacturing*, TRITA-IEO R 1996:4 (Stockholm, 1996), 11-14.

[17]Bengt-Åke, Lundwall, ”Explaining Interfim Cooperation and Innovation: Limits of the Transaction-Cost Approach”, in: Gernot Grabher, ed., *The Embedded Firm: On the Socioeconomics of Industrial Networks* (London: Routledge, 1993), 58.

[18] Wesley M. Cohen & Daniel A. Levinthal, "Absorptive Capacity: A New Perspective on Learning and Innovation", *Administrative Science Quarterly* 35 (1990), (128-52,)128.

[19]Cohen & Levinthal, 129.

[20]ASEA was in 1988 merged with the Swiss BBC into ASEA Brown Boveri (ABB), and the Swedish State Power Board is since 1992 divided into a wholly state owned power producing company known as Vattenfall and a grid administration Swedish Power Grids (Svenska Kraftnät).

[21]For a description of this first "battle of the currents", see: Hughes 1983, 106-139; Louis C. Hunter & Lynwood Bryant, *The Transmission of Power*, vol. 3 of *A History of Industrial Power in the United States, 1780-1930* (Cambridge, Mass., 1991), 243-72.

[22]Hunter & Bryant, 246, 255.

[23]Hunter & Bryant, 254.

[24]The term "second battle of the currents" are from: Mats Fridlund & Helmut Maier, "The Second Battle of the Currents: A Comparative Study of Engineering Nationalism in German and Swedish Electric Power, 1921-1961", Working Papers from the Department of History of Science and Technology 96/2 (Stockholm: KTH, 1996).

[25]*Svenska Vattenkraftsföreningens tolfte ordinarie årsmöte den 29 april 1921* (Stockholm, 1921), 68.

[26]A. R. Angelo & W. Rung, "Transmission of Electric Power from Norway to Denmark", 5 vols., *Transactions of the First World Power Conference* (London, 1924), vol. 3, 472-85; George Viel, "Étude d'un réseau 400 000 volts", *Revue Générale de l'Électricité* 28 (1930], 729-44; Ernst Schönholzer, "Ein elektrowirtschaftlisches Programm für Europa" *Schweizerische Technische Zeitschrift* (1930], 387.

[27]Helmut Maier, *Erwin Marx: (1883-1980) : Ingenieurwissenschaftler in Braunschweig, und die Forschung und Entwicklung auf dem Gebiet der elektrischen Energieübertragung auf weite Entfernung zwischen 1918 und 1950*, Diss. (Stuttgart, 1993), Ch. 4.1.2.

[28]Waldemar Borgquist, "Tendenserna inom den moderna kraftförsörjningen", *ERA* 3 (1930), 95.

[29]Nathan Rosenberg, "How Exogenous is Science?", in: idem, *Inside the Black Box*, 143-47; idem, ”Science and Technology in the Twentieth Century”, in: Dosi, Giannetti, & Toninelli, 64-65. – Although it is not going to be discussed here, the development of the HVDC technology is also a good example of "science as applied technology", see: Svante Lindqvist, ”Spatial Networks of Technological Change: Social Mobility between Industry and University”, in: *The Curt R. Nicolin Seminar: Knowledge as Substitute for Natural Resources* (Stockholm: KTH, 1994).

[30] Wesley M. Cohen & Daniel A. Levinthal, "Absorptive Capacity: A New Perspective on Learning and Innovation", *Administrative Science Quarterly* 35 (1990), (128-52,)128.

[31]"The History of D.C. Transmission: Part III", *Direct Current* 7 (1962), 230; "The History of D.C. Transmission: Part II", *Direct Current* 7 (1962), 61.

[32]Holmgren, 20.

[33]James E. Brittain, *Alexanderson: Pioneer in American Electrical Engineering* (Baltimore, 1992), 203.

[34]The History of D.C. Transmission: Part IV", *Direct Current* 8 (1963), 3-4; Maier 1993, 106; Maier 1993, 106-7.

[35]Maier 1993, 107-8.

[36]Maier 1993, 19.

[37]Maier, 298.

[38]"Högspänd likström även från Asea: von Platens system får svensk konkurrent", *Svenska Dagbladet*, 17/2 1934, 3.

[39]"The History of D.C. Transmission: Part IV", *Direct Current* 8 (1963), 4.

[40]Quoted in: "History of D.C. Transmission: Part IV", 5.

[41] The MAR is a vacuum tight vessel filled with mercury gas that has a pool of liquid mercury in its bottom and in its top one or several iron or graphite rods. In operation a direct current is generated through

an electric arc burning in the mercury gas between the cathode and anode. A fuller explanation of the mercury-arc rectifier is that a continuous direct current is generated in the form of an electric arc burning in the mercury gas between the liquid mercury (acting as an electron emitting cathode) and the rods (electron absorbing anodes). The continuos direct current is generated from AC with three phases (currents) through the fact that an anode gets ”blocked” when the alternating current becomes negative and instead the current is flowing in (electrons emitted by) one of the other anodes that is experiencing a positive AC-phase.

[42]”Protokoll hållet vid konferens den 29 och 30 december 1925”, 1, *ABB Central Archives (ABBCA)*, D:N7 02-005 [361/D-1002], Direktionskonferenser: Protokoll 1921-1932 (Ing. Hambergs).

[43]Nils Göte Håkansson, *Historik för lågspända jonventiler, 1927-65* (Ludvika, 1983), 1:5.

[44]Hendrik Rissik, *Mercury-Arc Current Converters: An Introduction to the Theory of Vapour-Arc Discharge Devices and to the Study of Rectification Phenomena* (London, 1935), 4.

[45]Rissik, 4-5. [Nils-Göte Håkansson], ”Försöksliriktaren: Jonventilepokens inledningsskede”, LFA 151A (Ludvika: ASEA, 1977), 17, 26, *Archieves of Tekniska Museet (TMA)*, 3771, IVA's Teknikhistoriska råds intervjuer, Uno Lamm.

[46]Håkansson 1983, 1:17.

[47]”Intervju med Uno Lamm”, 1/7-75, 1, *TMA*, 3771, IVA's Teknikhistoriska råds intervjuer, Uno Lamm.

[48]”Intervju med Uno Lamm”, 1/7-75, 2, *TMA*, 3771, IVA's Teknikhistoriska råds intervjuer, Uno Lamm;Katherine Wollard, "Uno Lamm: inventor and activist", *IEEE Spectrum* 25 (March 1988), 44.

[49]Håkansson 1983, 3:11.

[50]J. F., "Något om den styrda kvicksilverventilens möjligheter vid omvandling av elektrisk energi", 21/11-1932, s 1, *Vattenfall Väst Archieves (VVRA)*, HK, Diarieförda handlingar, 1932:349 Föredrag om likriktare.

[51]Lindén till Edström, 21/7-32, 2-3, *ABBCA*, D, 526/1448, Diverse extern korrespondens: 1930, 1932.

[52]Uno Lamm, "Kraftöverföring med högspänd likström: Den tidiga utvecklingen. Jonventilepoken", in: Barnevik, Percy, et al., *Teknik i ASEA: 1883-1983* (Västerås: ASEA, 1983), 37.

[53]Lamm 1976, 4.

[54]Emil Alm, ”Le Système Glesum: Un système électromagnétique noveau pour la production et l’utilisation du courant continu a haute tension” *Conférence Internationale des Grands Réseaux Électriques a Haute Tension: Compte-rendu des travaux de la 8ieme Session,* 3 vols. (Paris, 1935), vol. 3., Report 133, Report 347, 1.

[55]Lindén till C.G. Langenskiöld, 7/10-33, *ABBCA*, D, 544/1472, Diverse extern korrespondens: 1933-1934; Ragnar Liljeblad, ”Utlåtande angående den av von Platenska uppfinningen av anordningar för genererande och utnyttjande av högspänd likström”, 4/10-33, 3-4, *ABBCA*, D, 544/1472, Diverse extern korrespondens: 1933-1934. Liljeblad 30 september and Herlitz and Dreyfuss in October. In Swedish: ”i stort sett, att problemet är tekniskt löst”

[56]”Protokoll fört vid konferens 18/12 1933”, 1, *ABBCA*, D:N7 02-001 [401/D-1110], Diverse sammanträdesprotokoll 1906-1938.

[57]Lamm 1976, 6.

[58]"Högspänd likström även från Asea: von Platens system får svensk konkurrent", *Svenska Dagbladet,* 17/2 1934, 3.

[59]Jan Berneryd, "Uno Lamm: Framgångar och baktändningar", *Polhem: Tidskrift för teknikhistoria* 10 (1992), 84; "Högspänd likström även från Asea: von Platens system får svensk konkurrent", *Svenska Dagbladet*, 17/2 1934, 3; Lamm 1976, 6.

[60]The idea was to ’draw out’ over a wider length the voltage in the MAR that accelerated the positive ions

that hit the anodes and in turn created the back fires. In this first MAR the drawing out of the voltage was accomplished through inserting in the MAR a semiconducting ’grading-electrode’. The back fires in the MAR mainly depends on positive mercury ions is bombarding the negative anode during the blocking period of the anode. This knocks out electrons from the anode material that are then creates a large current in the opposite direction to cause the short circuit. The voltage that accelerates the positive ions to enough energy to be able to knock out the electrons is concentrated to a very short distance around the anode. Lamm’s idea was to extend this distance in which the voltage were and through this draw out the acceleration of the ions to a longer distance which gave the ions larger probability to collide with neutral mercury atoms on their way to the anode. Through this the velocity of the ions were reduced so that they were not able to knock on string enough to knock out electrons from the anode.

[61]Uno Lamm, "Grundläggande problem vid högspänd likströmsöverföring", *Teknisk Tidskrift* 77 (1947), 309.

[62]Uno Lamm, "Mercury Arc Converter Stations for High Voltage D. C. Power Transmission", *The International Conference on Large Electric Systems (C.I.G.R.E.), 11th Session*, 3 vols. (Paris, 1946), vol. 1., Report 133, 28.

[63]Uno Lamm, ”Redogörelse för under år 1937”,18/2-38, *TM 1578*, 2, *ABBCA*, Tekniska Meddelanden, H:C1 03-018, TM 1550-1589.

[64]Å. Karsberg, ”Undersökningar av anodkonstruktioner för högspända likriktare: *Konfidentiellt*”, 23/3-38, 11, *ABBCA*, Tekniska Meddelanden, H:C1 03-018, TM 1550-1589; Uno Lamm, " Kraftöverföring med högspänd likström – ett utvecklingsarbete", in: *Företagande, ekonomi och teknik: Studier tillägnade Marcus Wallenberg* (Stockholm, 1949), 189.

[65]Glete 1984, 69.

[66]Anders Ekström, *Den utställda världen: Stockholmsutställningen 1897 och 1800-talets världsutställningar* (Uppsala, 1993), 268; Henrik Björck, *Teknikens art och teknikernas grad: Föreställningar om teknik, vetenskap och kultur speglade i debatterna kring en teknisk doktorsgrad, 1900-1927* (Stockholm, 1993), 38-42, 164. Björck’s perspective on nations competing through their technologies can also be found in the work of Peter Fritzsche: ”Nationalism and technology reinforced each other; progress was widely perceived as a great scramble among states in which there were unmistakable winners and losers.” (Peter Fritzsche, *A Nation of Fliers: German Aviation and the Popular Imagination* [Cambridge, 1992], 2-3).

[67]Glete 1984, 43. Also cf.: Ekström, 287.

[68]Glete 1984, 69.

[69]A. Olsson, ”Några litteraturdata rör kraftöverföring med högspänd likström”, 18/10-40, 1, 15, *Vattenfall Archives (VA)*, EBB, Allmänt, F1AA:3204, Storkraftöverföring:I-III.

[70]Borgquist till Sylwan, 27/7-40, 3, *VA*, KB, F1BA:8, ASEA:II.

[71]Uno Lamm, ”Tekniskt-ekonomiska skäl för och emot kraftöverföring med högspänd likström”, 11/12-40, *TM 1794*, 9, *ABBCA*, D, 500/1387, Diverse Extern och Intern korrespondens: 1940.

[72]Borgquist till Lamm, 1/4-41, 1-2, *VA*, KB, F1BA:8, ASEA:II.

[73]Borgquist till Lamm, 1/4-41, 2-4, *VA*, KB, F1BA:8, ASEA:II.

[74]Åke Rusck, "Svensk kraftförsörjning i dag och i morgon", i: *Morgondagens teknik: Aktuella problem och framtidsperspektiv inom teknik och naturvetenskap* (Stockholm: Teknisk Tidskrifts förlag, 1945), 155.

[75]Borgquist till ÖD m.fl., 11/5-42, 1-2, *VA*, EBB, Allmänt, F1AA:3204, Storkraftöverföring:I-III.

[76]Åke T. Vrethem, ”PM beträffande försöksanläggning for högspänd likström”, 8/10-43, 1, *VA*, EBB, Allmänt, F1AA:3204, Storkraftöverföring:I-III.

[77]"Isolationsstandard – Storkraftöverföring: ett svenskt-schweiziskt tankeutbyte", *Teknisk Tidskrift* 74 (1944), 18.

[78]Rusck till Elektrobyggnadskontoret, 11/6-42, *VVRA*, HK, F1ABC:68, Försöksanl. för högspänd likström 1942-1947.

[79]"The Development of a Valve", *Direct Current* 6 (1960/61), 224; Lamm 1976, 6-7.

[80]Borgquist 1968, 19.

[81]Lamm 1976, 2.

[82]”Avskrift: Avtal”, 20/12-43 & 28/12-43, 1, *VVRA*, DA, F1CC:1, Högspänd likström Juli - Dec 1944.

[83]Avskrift: Avtal”, 20/12-43 & 28/12-43, 3, *VVRA*, DA, F1CC:1, Högspänd likström Juli - Dec 1944.

[84]Sylwan 1944, 57.

[85]Helén, vol. 3, 105; Lamm 1949, 189.

[86]Blomqvist 1946, 21.

[87]Ragnar Lundholm, ”Likström genom jorden över långa avstånd”, *Teknisk Tidskrift* 77 (1947), 321.

[88]Uno Lamm, ”High Voltage Direct Current Transmission”, i: *Proceedings High Voltage Symposium* (Ottawa, 1956),Report 9, 9:10.

[89]Lamm 1976, 14.

[90]Lamm 1949, 194.

[91]Bjurling, 140.

[92]Bjurling, 140.

[93]Lundholm 1952/53, 82; Bo Rathsman & Ulf Glimstedt, *De tekniska och ekonomiska möjligheterna att överföra kraft från fastlandet till Gotland* (Stockholm: Vattenfallstyrelsen, 1949), 43.

[94]Lamm 1947, 311.

[95]Lamm 1947, 314.

[96]Bo G Rathsman, "Forskning bakom 380 kV systemet", *Teknisk Tidskrift* 84 (1954), 12.

[97]Rathsman & Glimstedt, *De tekniska*, 45.

[98]Walter Deines, "Elströmmens inverkan på havsfaunan", *ERA* 22 (1949), 108.

[99]Bo Rathsman & Ulf Glimstedt, *De tekniska och ekonomiska möjligheterna att överföra kraft från fastlandet till Gotland* (Stockholm: Vattenfallstyrelsen, 1949), 60, 62.

[100]Bo G. Rathsman, "Likströmsöverföringen till Gotland", *Teknisk Tidskrift* 84 (1954), 3.

[101]Uno Lamm, "Kraftöverföring med högspänd likström från fastlandet till Gotland", *Aseas Tidning* 42 (1950), 146.

[102]Lamm 1947, 311.

[103]Lamm 1947, 311-2

[104]Bo G. Rathsman & Sven Svidén, *Likströmsöverföringen från fastlandet till Gotland*, Blå-vita serien 15 (Stockholm, 1956), 12.

[105]Rathsman 1954, 7.

[106]Glete 1983, 175.

[107]My calculations from information in handwritten memos: ”P,M. angående kostnader i samband med försöksanläggningen för högspänd likström”, 31/12-59, & ”Sammanställning över gjorda investeringar och driftskostnader jämte pålägg och beräknad ränta”, n.d. but probably 1959, *VVRA*, HK, F1ABC:68, Kontrakt.

[108]Bo Rathsman & Ulf Glimstedt, "Elkraftöverföring till Gotland", *ERA* 22 (1949), 99.

[109]"Asea håller", 20.

[110]"Elkabel under Engelska kanalen", *Teknisk Tidskrift* 84 (1954), 556.

[111]"Elkabel", 556; Uno Lamm "Kraftöverföring med högspänd likström: Den tidiga utvecklingen. Jonventilepoken", i: Barnevik, Percy, et al., *Teknik i ASEA: 1883-1983* (Västerås: ASEA, 1983), 42.

[112]D.P. Sayers, M.E. Laborde & F.J. Lane, ”The Possibilities of A Cross-Channel Power Link between the British and French Supply Systems”, (Proof to be published in *Proceedings of the Institution of Electrical Engineers*, London, recieved 21/1-54), 4,

ABBCA, D, 1072/2059, Högspänd likström 1943-1957.

[113]"Elkabel", 556.

[114]Berneryd 1992, 86.

[115]Uhlmann & Engström, 31.

[116]"Asea håller tiden i kanalprojektet", *Vi Aseater* 23 (1960), No. 8, 20; "Likströmsöverföringen för Engelska Kanalen invigd", *Aseas Tidning* 54 (1962), 17.

[117]"Likströmsöverföring för Engelska Kanalen", *Teknisk Tidskrift* 89 (1959), 32.

[118]Uno Lammm, "ASEAs lansering av kraftöverföring med högspänd likström (HVDC) i USA", i: Barnevik, Percy, et al., *Teknik i ASEA: 1883–1983* (Västerås: ASEA, 1983), 111–18.

[119]Glete 1983, 287.

[120]Sven Lalander & Rolf Gradin, "Konti-Skan", *Teknisk Tidskrift* 92 (1962), 1189; "Konti-Skan: Ett verkligt kraftprojekt", *Vi Aseater* 28 (1963), No. 4, 6.

[121]"Konti-Skan: Ett verkligt kraftprojekt", 4.

[122]<u>Konti-Skan: Untersuchungen über die Voraussetzungen für eine dem Verbundbetrieb zwischen der BR Deutschland und den Skandinavischen Ländern dienende Hochspannungsverbindung / Studier av förutsättningarna för upprättande av en samkörningsförbindelse mellan Västtyskland och de skandinaviska länderna</u>, 2 vols. (Stockholm, 1962), vol. 1, 35, 51.

[123]"P,M. angående kostnader i samband med försöksanläggningen för högspänd likström", 31/12-59, & "Sammanställning över gjorda investeringar och driftskostnader jämte pålägg och beräknad ränta", n.d. but probably 1959, *VVRA*, HK, F1ABC:68, Kontrakt..

[124]"Europaväg för elkraften", *Vi i Vattenfall* 16 (1963), No. 3, 3.