environments

MDPI

Article

Industrial Energy Transitions and the Dynamics of Innovation Systems: The Swedish Pulp and Paper Industry, 1970–2010

Kristina Söderholm [1] and Patrik Söderholm [2,*]

1 Department of Business Administration, Technology and Social Sciences (ETS), History Unit, Technology and Social Sciences, Luleå University of Technology, 971 87 Luleå, Sweden; kristina.soderholm@ltu.se
2 Department of Business Administration, Technology and Social Sciences (ETS), Economics Unit, Luleå University of Technology, 971 87 Luleå, Sweden
* Correspondence: patrik.soderholm@ltu.se

Received: 24 August 2020; Accepted: 9 September 2020; Published: 10 September 2020

Abstract: This article provides a sectoral innovation system perspective of the development of energy efficient and clean process technologies in the Swedish pulp and paper industry. Specifically, the analysis elaborates the importance of knowledge development, actor networks, and institutions (including policy) for progressing and diffusing novel technologies related to energy use. The empirical analysis also sheds light on how significant changes in the sectoral innovation system have influenced the relevant research, development and demonstration activities in the Swedish pulp and paper industry over the period 1970–2010. The results are based on various sources—e.g., industry magazines, reports from industrial consultants and associations, minutes from meetings—and illustrate the importance of well-functioning innovation systems for successful technological development and diffusion processes. They display, in particular, the importance of joint, industry-wide R&D activities, trust-based state—industry relationships, government R&D expenditures, and intense information sharing. One important implication is that the role of policy stretches beyond the funding of basic R&D. Policy also involves measures that strengthen existing actor networks, build competence, and secure the existence of research institutes that provide a bridge between basic knowledge generation (at the universities) on the one hand, and industrial application on the other.

Keywords: energy transitions; energy efficiency; R&D; pulp and paper industry; policy

1. Introduction

This article addresses the question of how a transition towards radically lower energy use and zero-carbon production processes in the industrial sectors can be achieved. Such a transition cannot solely build on existing, "off-the-shelf", technologies; it requires that new technologies be developed, optimized and diffused among industrial firms [1,2]. Such a process ought in turn to build on the establishment of a network of collaborating actors, i.e., institutes, producers, equipment suppliers, and universities, as well as on policy interventions through the (co-)funding of R&D programs and pilot and demonstration plants [3,4]. Moreover, the transitions towards more sustainable production patterns are often characterized by relatively long development periods, during which sometimes novel value chains and institutional arrangements must be put in place and aligned with emerging technologies [5].

In the light of the above, it is useful to draw on the lessons from sustainable energy transitions in the past. The purpose of this article is therefore to analyze the development of energy efficient and carbon-free process technologies in the Swedish pulp and paper industry over an extended period, 1970–2010. The analysis focuses on key prerequisites for progressing and diffusing novel technologies in this industry, i.e., knowledge development, information sharing, actor networks and public policy support. Significant changes in these prerequisites over time are highlighted. Given this purpose, we are not able address details about specific technologies and processes; instead, the focus lies on the institutional and organizational circumstances that have made these possible in the first place.

Related previous research about industrial energy transitions has had a strong emphasis on the contemporary barriers and driving forces for improved energy efficiency and carbon dioxide reductions, including the role of different types of policies (e.g., [6–9]). The historically oriented studies have been biased towards quantitative assessments of industrial energy use, addressing the role of fuel prices, productivity improvements, structural change and shifts in demand [10–14]. Still, the latter work has primarily devoted attention to the outcomes of technological change (e.g., in terms of productivity improvements and fuel choices), without, however, investigating in detail what made sustainable technological change possible in the first place. Both Bergquist and Söderholm [15] and Ottosson [16] provide qualitative analyses of the energy transition of the Swedish forest industries. However, the present article differs from this research in that it: (a) devotes explicit attention to the prerequisites for R&D and demonstration activities relating to energy efficient and zero-carbon production processes; (b) acknowledges the sources and the consequences of key changes in these prerequisites over an extended time period (1970–2010).

There are at least two reasons for why this historical approach could contribute with relevant, generic lessons about how the organization of, and the support of, knowledge development and transfer could affect the prospects of contemporary energy transitions in the industrial sectors. First, industry representatives and policy makers increasingly emphasize the importance of management practices and policy interventions in the form of, for instance, government support of knowledge development and diffusion, network management activities, information sharing, and funding of pilot and demonstration plants [17]. Such best practices and policies indeed dominated the energy transition of the Swedish pulp and paper industry, in particular during the 1970s and the 1980s [15]. The outcomes in terms of energy efficiency improvements and reduced fossil fuel use were notable.

Specifically, the fossil fuel fraction out of total fuel use decreased from 43 to 7 percent over the period 1973–2011 [13]; this implied an 85 percent reduction in the emissions of carbon dioxide. The energy efficiency of Swedish pulp and paper mills also improved significantly during this period. For instance, even though the entire sector's energy use remained more or less constant over the 1970–2000 period, pulp production increased by 70 percent and paper production by 127 percent [18]. The energy performance of Swedish mills has, overall, been higher compared to mills in countries such as Brazil, Canada and the USA [19]. For these reasons, it is useful to learn about how these practices and policies were established, maintained and altered, and what lessons can be drawn in the context of contemporary policy ambitions.

Second, the existing research on sustainability transitions has emphasized how the design and implementation of effective mixes of policy instruments is a complex and highly context-specific undertaking [20]. It is therefore important to abstain from oversimplified normative notions about the impact and desirability of policy mixes regardless of context, including the existence of various institutional preconditions as well as different types of actor networks and forms of cooperation [21]. Furthermore, public policy is not static, and important policy responses may emerge from systemic imbalances; these could even coevolve with the sectors that policy makers intervene in [22]. In this context, our long-term, historical approach provides an opportunity to understand how important changes—in industry practices and in institutions and policy—have affected the direction and the nature of the industry's knowledge generation and technology diffusion activities.

The article proceeds as follows. In the next section, we present an analytical framework, rooting in the so-called sectoral innovation system (SIS) literature, and we link this perspective to the various iterative phases of the technological development process (i.e., basic R&D and concept development, applied R&D and pilot and demonstration projects, and technology diffusion). Section 3 presents the methods and materials used, while Section 4 outlines the key empirical findings. The article ends with a discussion of important implications, e.g., for policy in the context of ongoing sustainability transitions (Section 5), and a brief concluding section outlining some important avenues for future research (Section 6).

2. Conceptual Points of the Departure and Analytical Framework

The analysis in this paper departs from the so-called sectoral innovation system (SIS) approach [23]. The SIS framework addresses the rate and the types of innovation, as well as the organization of innovative activities in sectors. The notion of an SIS relates to two strands of the literature. The first is evolutionary theory, which views innovation as a dynamic and interactive process among a wide variety of actors [24]. Knowledge and learning are key elements in the change of the economic system, and heterogeneous agents act, learn and search in uncertain and changing environments. However, their behavior, learning and capabilities will be constrained by technology, knowledge base and institutional context, which all tend to vary across sectors [25]. The second strand of literature is the innovation system approach, which stresses that innovation is an interactive and collective process among a wide variety of actors [26]. In other words, the innovative performance of a given sector (or economy) depends not only on how the individual actors perform in isolation, but also on how they interact with each other in terms of knowledge generation and diffusion, including their interplay with societal institutions [27].

Following Malerba [25], the SIS concept consists of three key building blocks: the knowledge and technological domain, actors and networks, and institutions. The knowledge and technological domain is the domain in which the boundaries of the system are defined. Knowledge and basic technologies constrain the behavior and organization of firms, but these boundaries change over time (not least as a consequence of innovation). The actors and networks are sector-specific as well, and the actors are heterogeneous, including, for instance, producing firms, equipment suppliers, users, universities, research institutes, government agencies, etc. An SIS is as such composed of webs of market and nonmarket relationships among actors with typically different beliefs, competences and behaviors. These relationships and the resulting actor networks will thus integrate complementarities in knowledge, capabilities and specialization [28]. Furthermore, the societal institutions shape actors' cognition, actions and interactions, and include formal rules (e.g., immaterial rights, environmental regulations, product standards, policies), and informal rules (e.g., norms and codes of conduct). The institutions are often national (e.g., the patent system), but they are often sector-specific (e.g., business practices, product standards) [25].

Figure 1 displays our analytical framework, illustrating the article's focus on how knowledge is generated and diffused in industries, not least in energy-intensive process industries. The framework also addresses how actor networks and collaborations, and policy and institutions make this possible. Figure 1 links the structural components of a (SIS) to the process of technological development, thus also recognizing that the relationship between basic R&D and diffusion of novel technology is a complex and highly iterative process with several feedback loops. Two issues are worth noting.

First, pilot and demonstration projects may play several important roles, not least in verifying, optimizing, upscaling and improving the performance of new technology [29]. In other words, such projects (and plants) represent bridges between basic knowledge generation on the one hand, and industrial application and commercial adoption on the other. Second, the process is iterative in that there are key feedback mechanisms between all stages of this process. This feedback can generate learning where firms, suppliers and researchers can contribute to the development in various ways. For instance, learning-by-doing refers to the learning that takes place as the production is up-scaled, including tacit knowledge acquired during manufacturing. Learning-by-using instead refers to the learning that occurs in connection with the use of the products, i.e., as customers give feedback to suppliers and thus devise new ways to use and/or integrate new technology in existing production processes [30]. Thus, technological progress requires both R&D and learning and for this reason, R&D programs should typically not be designed in isolation from practical application. For instance, the gradual diffusion of certain technologies can reveal new areas where additional R&D would be most productive, and industrial companies may also cooperate directly with the university sector.

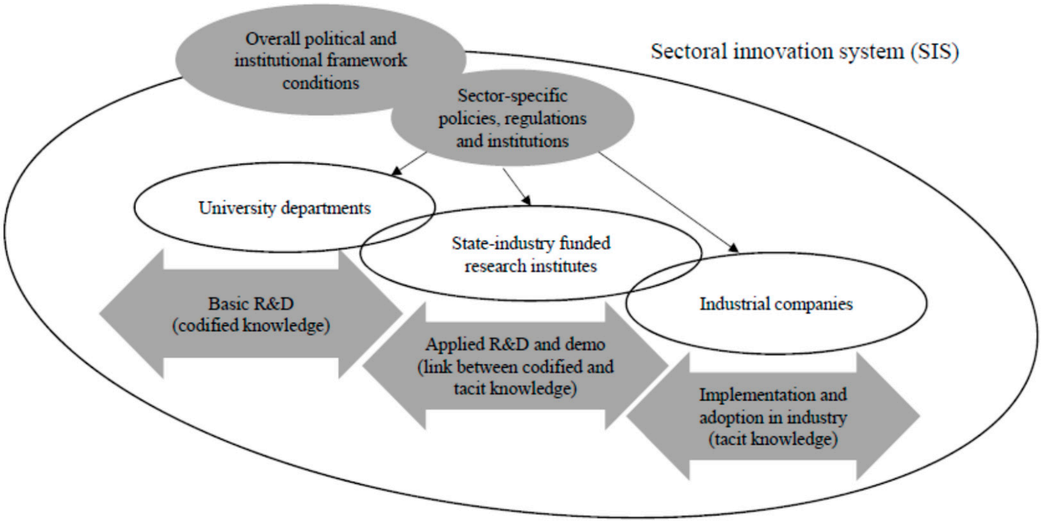

Figure 1. Analytical Framework: Sectoral Innovation System and Technological Development.

The above implies the significance of several overlaps—and iterative collaborations—between the various types of actors in the innovation system. R&D collaboration provides an opportunity to share risks and costs, as well as exploit complementary know-how between companies [31]. Cohen and Levinthal [32] showed that the interaction between proprietary and external knowledge is highly important for such collaborations and the overall performance of an SIS; companies must possess the ability to recognize and make use of information generated through R&D and learning—the so-called absorptive capacity. In this respect, the industry research institutes could well play an important intermediating role through applied R&D and pilot projects as well as efforts aimed at transferring and diffusing knowledge within the industry.

Put differently, while universities generate and transfer codified knowledge, the industrial firms apply and use such knowledge, and thus generate mainly tacit knowledge. In between, however, the industry research institutes play a key role. These also produce and transfer codified knowledge, but in addition to this, they often assist in stimulating knowledge transfer and application in industry [33]. This notion is particularly valid in the context of the pulp and paper industry; in this sector, the knowledge formation process does not only concern R&D, but also technology demonstration and tests [15], as well as synthetical development activities for which system integration is very important [34].

Policy typically needs to build on a mix of instruments in order to address market imperfections as well as various types of structural and transformational system failures [35]. These include the long-term risks of R&D and technology demonstration, environmental externalities, absence of diversity in the actor base, and the lack of collaboration among key actors. For this reason, policy instrument mixes will often facilitate the provision of basic and applied R&D, but also support the diffusion of novel technologies as well as the different functions operating at the innovation system level [3,36]. The latter includes providing infrastructure, facilitating the alignment among actors and stakeholders, stimulating strategy and vision development, as well as the establishment of effective organizational solutions. As noted above, some policies may be uniform across sectors while others, e.g., government support of given technological fields, are typically sector-specific. Sector-specific policies could be motivated given that different sectors and types of technologies tend to face unique learning processes and bottlenecks [2].

Finally, sectoral innovation systems evolve over time. The type and the structure of relationships and actor networks may change, e.g., as a consequence of changes in the knowledge base, the learning processes, demand and institutions, among other things [23]. Changes over time in turn results in a coevolutionary process of the various elements of the SIS, i.e., knowledge, actors, technology and institutions. Given its focus on a 40-year-long period, this article enables an analysis of such changes. In the article, we highlight how often-external factors have induced changes in the SIS. Still, the focus does not lie on elaborating the sources of such changes, e.g., the consolidation and globalization of the industry. Instead, we investigate what these changes have implied for managerial and policy decision-making in the country.

3. Material and Methods

The analysis builds on qualitative historical case study method focusing on the energy transition of the Swedish pulp and paper industry over a 40-year-long period. Previous innovation system research has emphasized the historical perspective, and that important lessons could be drawn from studying past transitions [37]. The Swedish pulp and paper industry case is interesting not only since it illustrates excellent track records in terms of energy efficiency improvements and carbon dioxide reductions, but also because it involves an interesting history of industry cooperation in energy R&D, which is in turn actively supported by the state [15]. In particular, during the 1970s and the 1980s, there was a strong focus on R&D and pilot tests as engines of change, and per capita government spending on energy R&D and demonstration activities was typically significantly higher than that of most other Organization for Economic Co-operation and Development (OECD) countries [38].

The Swedish pulp and paper case study relies on a number of first-hand sources, including: (a) industry magazines; (b) various policy documents (e.g., government bills, public inquires); (c) reports from selected government authorities (such as the Swedish Energy Agency, Swedish Ministry of Industry, and Swedish Industry Agency); as well as (d) reports and committee minutes from various industry organizations, including the Swedish Pulp and Paper Research Institute (STFI), the Swedish Pulp and Paper Mill Association (SCPF) and the Pulp and Paper Research Foundation (the latter is based on material archived at Stockholm Centre for Business History). As noted below, the STFI, in particular, played a key role in the industry's energy transition, although its role changed over the studied period. The history of the STFI and other key institutes has been documented also in previous reports and books [39–41]. In terms of industry sector magazines, we consulted all issues of Svensk Papperstidning (Swedish Paper Journal) from 1970 and onwards.

In Section 4, we review the key experiences from the energy transition of the Swedish pulp and paper industry focusing on initiatives initiated during the 1970–2010 period divided into three phases (introduced by a brief historical background). The key rationale for dividing the full period into these shorter phases was based on the emergence of significant changes in the relevant sectoral innovation system as well as on changed priorities in the public and private R&D agendas.

4. Results

4.1. Historical Background

The emergency situation during the Second World War induced Swedish pulp and paper mills to identify more energy-efficient production practices. Several technological improvements did contribute to a more efficient use of heat in paper mills, such as through more enclosed dryer sections, refined heat recovery systems, and more efficient steam and condensate systems [42]. For instance, at a typical kraft pulp mill almost 90 percent of the heat demand was supplied by the burning of black liquor and bark (and thus only roughly 10 percent by oil). Thus, prior to the advent of the oil crises in the 1970s, Swedish (and also Scandinavian) mills were more energy efficient compared to most of the North American ones (where gases were generally not recovered for heat generation).

An important reason for this was that environmental protection and energy efficiency often constituted different sides of the same coin, and early on, the strategy of the Swedish pulp and paper industry involved responding to the environmental pollution challenges jointly within collaborative (industry-wide) R&D platforms. A number of R&D platforms were established, and during the 1940s and 1950s, the industry decided to deal with pollution abatement preventively, i.e., with a focus on internal process changes in favor of end-of-pipe technology [43].

As noted below, the Swedish approach also built on consensual and trust-based relationships between government and industry. This cooperative approach, also frequently involving generous government R&D grants, remained intact until the end of the 1980s. A large chunk of the investments in environmental protection undertaken since the 1940s and onwards, implied energy savings. For instance, the further development of oxygen bleaching, as well as improvements in process system control, led to both energy savings and reduced pollution due to the recovery of the dissolved lignin for energy generation and lowered emissions of organic material [44].

4.2. The Cooperative State–Industry Response to the Oil Crises, 1970–1985

The Arabic oil embargo and the soaring oil price in 1974 had significant impacts on the global economy, and not least on energy-intensive industries. Since the Swedish pulp and paper industry had far from neglected energy issues during the 1950s and the 1960s, it was relatively well-prepared for this external shock.

In January 1973, the sector had established a standing energy program committee, with the objective to encourage the development and adoption of built-in energy efficient technologies, which improved mill performance [45]. Equally important purposes included collection and dissemination of information within the sector about state-of-the-art technology and important developments, and the appointment of representatives to investigate special tasks and represent the industry in public bodies and inquires [40]. Specifically, in-depth systematic surveys of the energy use and performance of all Swedish pulp and paper mills were conducted [45,46], first in 1974 [47], and then onwards every fifth year. The early surveys were used as central references in an international cooperation among pulp and paper mills, coordinated by the International Energy Agency [48].

In another project initiated by the committee, best available technologies in the manufacturing of four standard grades were investigated, with the aim to provide a handbook for technicians in the industry [45,46]. This work resulted in four reports outlining model mills in terms of energy efficiency potentials and measures in both existing and new paper mills [49–52]. The findings from both the surveys and the technical assessments were widely diffused in the sector, and individual mills could draw from the experiences and skills of the entire pool of process engineers and technicians in the country [53]. This was facilitated by the long-standing tradition of intraindustry collaboration within the Swedish pulp and paper industry, and not least the often-positive attitude towards information sharing [54].

Moreover, starting in 1973, the standing energy committee compiled a list of key R&D and demonstration projects, e.g., focusing on back-pressure turbine generation and the incineration of bark and other forest waste [45]. With the advent of the first oil crisis in 1974, this work intensified, and in 1977, 50 energy projects had started or been proposed [55]. This mobilization included both low-hanging energy savings projects such as so-called “go-through” procedures, i.e., simple energy mapping activities [56], but increasingly also projects aimed at developing and improving new technology enabling either the phase out of oil (27 percent) or increased energy efficiency (73 percent) [49–52]. When pursuing such development activities, individual mills contributed by testing new machinery and processes in full-scale, as well as through own applied R&D. The Swedish pulp and paper industry also attempted to engage university departments and encouraged these to apply for government funding [57].

The Swedish government assumed a rather active role in these efforts, not least by providing funding to the industry research institutes, such as the STFI, as well as to specific industry-wide

R&D projects. In Sweden, the relationship between state and industry was very much trust-based; it rested on collaboration and consensus-seeking, i.e., a corporatist, negotiated form of governance [58]. This included the state's engagement in the industry research institutes with the purpose of securing the competitive strength of the country's industry. This model stands out in an international comparison, although inspiration also came from Germany [59]. For instance, Smith [60] notes that shared and collective R&D in the US pulp and paper industry was limited during this period, as were joint state–industry R&D projects. This, it is argued, handicapped environmental innovation in the US industry. The Swedish model, very much based on intense cooperation between industry, research institutes, and universities, was recognized internationally [61].

Following the first oil crisis in 1974, the Swedish government greatly increased its commitment to energy R&D. The so-called energy program was launched in 1975 [62] and additional funding was granted to individual companies, research institutes and universities. Basic and applied R&D, not least various pilot and demonstration plants for oil substitution, constituted key ingredients of this industry-focused policy e.g., [41,63]. The development and installation of new processes could be subsidized by as much as 50 percent [53].

Figure 2 displays government R&D expenditures on industrial energy use and efficiency; these data cover also support pilot and demonstration plants. Government support of energy R&D in the industrial sector was high during the period 1975–1985, both compared to later periods as well as in relation to other countries e.g., [38]. While Figure 2 displays government R&D expenditures to all industrial sectors, it is worth noting that initially the pulp and paper industry did receive the largest chunk of the support. For instance, during the 1975/76 period, almost 40 percent of the government support of pilot and demonstration plants were allocated to the pulp and paper industry [64]. As further discussed in Section 4.3, this changed in the late 1980s as the universities' share of industry-focused government R&D increased a lot, and at the expense of significant cuts in related grants to the private industry [63].

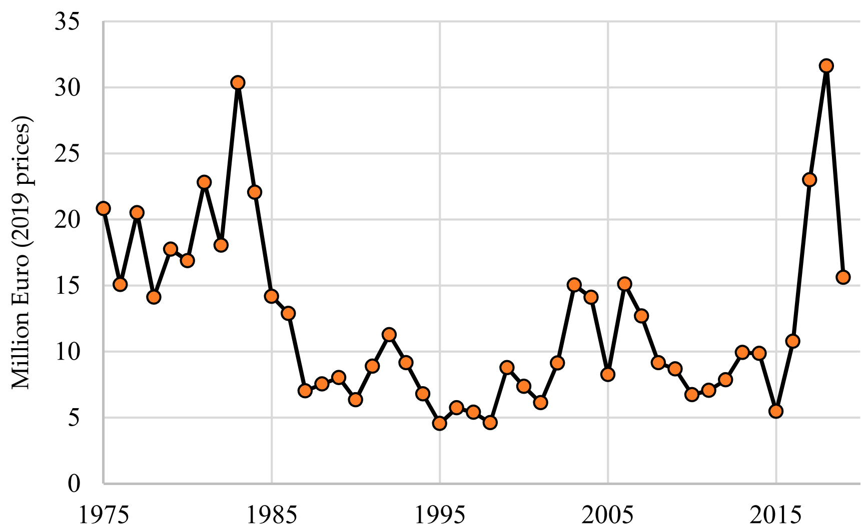

Figure 2. Government R&D Expenditures Relating to Industrial Energy Use in Sweden, 1975–2019 Source: International Energy Agency [65]. The data include national government funding to support the installation of pilot and demonstration plants.

Much of the basic knowledge needed to generate energy from burning internal organic residual products (i.e., black liquor, bark), and through back-pressure turbine power generation, had been established before the first oil crisis, but the soaring oil prices and government subsidies for pilot and demonstration projects increased the incentives for exploring these options further [66,67]. Yet other pilot projects involved more efficient heat recovery, and improved press and drying technologies [68].

Nevertheless, the responses to the oil crises also involved more novel R&D efforts and solutions. The energy R&D and demonstration activities in the Swedish pulp and paper industry could use—and benefit from—the R&D platforms and state–industry relationships that had been established over a long period. The combination of government support and industry-wide R&D cooperation implied a lower risk for the companies, and the STFI represented the key collaborative arena in the industry's responses to the oil crises. From the 1960s and onwards, every member of the SCPF, i.e., every single Swedish pulp and paper mill, had to contribute to the funding of the STFI's R&D activities [39]. Marklund [40] notes how the STFI represented a bridge between basic R&D on the one hand, and industrial adoption on the other (see also [69]).

> The protective shelter of the institution, through its controlling of large quantitative and qualitative resources, has been essential for the particular learning in R&D that took place there—and this also attracted good researchers (Marklund [40], p. 186).

One of the most significant achievements, where the STFI and its researchers played a key role, was the development of so-called modified continuous cooking. During the 1970s, the STFI had initiated projects involving improvements of the pulp bleaching process; the aim was to decrease the use of chemicals and increase the level of delignification in the digester. In the early 1980s, novel methods of cooking the wood chips that result in pulp with low levels of lignin were developed. This implied that the released lignin and other organic substances in the spent cooking liquor could be used for energy production in the recovery boiler [70]. This helped reduce the use of external energy sources and chemicals needed in final bleaching, thus also reducing the emissions of chlorinated substances from bleaching [71].

The STFI was also one of the key collaborative R&D arenas in the development of improved process control and optimization [72], such as for washing and in the lime kiln and recovery boiler [73]. Marklund [40] notes that the industry's approach to process control was empirical rather than theoretical, largely due to the large number of connections and their complexity. In other words, these development activities can be described as learning-by-doing processes, and involved collaborations with key equipment suppliers (e.g., ASEA). In the case of washing, experiments were conducted in cooperation with Korsnäs (today BillerudKorsnäs), and this resulted in reduced process variations (and, as a consequence, a lowered energy use). The new system became standard in the industry [39]. Corresponding improvements were made with respect to the energy performance—and overall stability—of the lime kiln, this time in collaboration with the Mörrum mill.

Equipment suppliers were also heavily involved in the development activities led by the STFI, such as in a project on developing process control systems for recovery boilers [39,74]. This project received government grants, involved one supplier of recovery boilers and practical tests at the Mönsterås mill. The new system made it possible to achieve a higher stability in the energy load (as well as reduced emissions of sulfur dioxide), and it was widely diffused in the industry. By the end of the 1980s, at least 60 percent of the recovery boiler capacity in the country involved some type of process control [39]. Marklund [40] remarks that overall process control technologies diffused more rapidly in the pulp and paper industry compared to other process industries. One reason for this is that standardized system solutions are easier to implement in the pulp and paper industry due to the presence of several subprocesses with similar designs across mills. Still, Marklund [40] argues, the rapid diffusion of such technologies should also be attributed to the relatively open attitude towards information sharing in the sector at the time.

The above progress in the field of process control and optimization also helped improve the competitiveness of the pulp and paper industry [75]. During the 1990s, process system technologies became increasingly computerized, and several types of new information systems were adopted and tested [76].

4.3. Partial Dismantling of the Cooperative Approach, 1985–2000

During the 1980s, the conventional wisdom in the Swedish pulp and paper industry was that the past R&D cooperation had been a major source of success for the sector, and in 1985, the retiring director of the STFI called for widened cooperation in the future [73]. For instance, he emphasized the importance of further engaging equipment suppliers and individual companies with STFI activities, e.g., by pooling resources from mills facing similar problems. In addition, he argued, it was essential to establish a collaborative R&D arena for researchers at the STFI and the university departments, respectively. A related argument for the importance of industry R&D cooperation was put forward by a cellulose technology professor in 1987 [77]; he emphasized the important role that equipment suppliers had had for developing the competitiveness of the country's pulp and paper industry. While both Stockman and Croon praised the role of STFI as a key collaborative arena for industry-wide R&D, they also sensed that the industrial companies had become less keen on sharing R&D resources. The Swedish pulp and paper industry, Croon argued, suffered from "conservative destructiveness" [77].

The prerequisites for R&D cooperation did indeed change during the second half of the 1980s, not least in the form of an altered perception of the role of the collective research institutes such as the STFI. This was in turn a result of both political change and new sector-internal priorities. Changes in the political sphere contributed to a weakening of the industry research institutes; government support of the universities increased substantially during the 1980s and the 1990s, and very much at the expense of lower funding to the institutes [63]. Figure 2 shows that the total government support of industrial energy R&D was comparatively low during the entire 1985–2000 period. Pettersson [78] explains that, at the time, this policy shift was partly rooted in the notion that the university sector was expected to take more responsibility for applied R&D and innovation, and also collaborate more with industrial sectors [79].

Some scholars even claim that the Swedish corporatist, consensus-seeking approach to state–industry relationships became weaker during the 1990s and onwards [80], although others maintain that it remains a relevant description of the current Swedish policy model [81]. In any case, during the 1990s, there was less room for the collective industry research institutes, not only for the STFI but also for corresponding institutes in other industrial sectors such as the mining and metals industry. This, industry representatives argued, constituted a particular threat for R&D on challenges shared by industrial companies, not least for challenges related to energy savings and limited environmental impacts [82]. Moreover, fears were expressed that an efficient interaction between basic and applied R&D would become more difficult to realize [39].

At the sector level, structural changes in the pulp and paper industry led to a consolidation, and the emergence of larger companies [83], which also considered it rational to conduct more of the applied R&D in-house. The STFI was therefore induced to take on more basic R&D endeavors, but this did not benefit the smaller companies, which as a result faced fewer incentives to contribute to STFI activities. Consequently, in 1993, the mandatory participation in the STFI platform ceased, and it was replaced by a model based on bilateral R&D agreements [39]. Moreover, the Swedish pulp and paper companies also began to increasingly prioritize cooperation with university departments, in part due to less government R&D funding being allocated to the STFI [39], but also as a way of attracting and recruiting new staff, such as process engineers.

In spite of these political and structural changes, the STFI retained its position as one of the key actors in the case of energy R&D for the pulp and paper industry, but in a partly new disguise. Three changes are worth noting. First, in 1993, the STFI went through an organizational change, and one important outcome of this was a clearer distinction between the basic and applied R&D departments. Eriksson [39] refers to this as the emergence of "a moat" between the two departments. Second, since the industry started to collaborate more directly with university departments, there was often more direct competition between the STFI and the university sector. In this way, the STFI in part lost its role as a bridge between basic R&D and industrial applications. Third, the emerging arenas for R&D cooperation were project-based rather than being characterized by continuous, and occasionally more long-run, development activities under the auspices of the STFI [39]. One relevant example of this development is the launch of a new joint research project—the so-called KAM project—involving the STFI, several universities and a few industrial companies. It ran over two shorter periods, 1996–1999 and 2000–2002, respectively [84–86], and the main funding came from the government.

Around 1990, the Swedish pulp and paper industry began to focus more on achieving a more efficient use of electricity, in part a natural consequence of the increase in electricity use at the expense of fossil fuels during the early 1980s. These R&D activities focused on, for instance, improved process control [72], and reduced electricity use through eliminated wear losses in large pumps [87]. In terms of realized electricity savings, the most significant outcomes of these—and related—efforts primarily became evident after the turn of the century [13]. From the late 1990s and onwards, there was also further interest in internal electricity generation through investments in so-called backpressure turbines [88]. The development towards increased internal electricity generation was largely policy-driven; it was induced by the electricity market reform (1996), the green certificate scheme for renewable electricity (2003), and the European Union emissions trading scheme for carbon dioxide (EU ETS) (2005) [89]. At a general level, government support of energy R&D also helped promote a more efficient use of electricity in the industry. Nevertheless, its role was more modest during the late 1980s and early 1990s compared to the 1975–1985 period (see Figure 2), in part as a result of the deep macroeconomic recession in Sweden in the early 1990s.

The above-mentioned KAM-project also illustrates the reallocation of funding for R&D efforts addressing energy potentials, resource efficiency and the increased recovery of excess energy at pulp mills [90]. This involved, for instance, research on black liquor gasification [91,92], where the spent cooing liquor from a chemical pulp mill (or solid biomass) can be used to produce heat, electricity, or synthesis gas (syngas), which in turn can be upgraded to various fuels [93]. Still, a lot of attention was also devoted to closing the cycles through improved process integration. In a follow-up R&D endeavor—the so-called FRAM project (2003–2004)—these development efforts focused much on the extraction of lignin as this permits a capacity increase in pulp production. In other words, less attention was devoted to using the syngas (or the lignin) to diversify the sector's product portfolio, e.g., by producing biofuels such as ethanol or DME (dimethyl ether), green chemicals and/or carbon fibers [94,95]. Quite a few people in the sector argued that this R&D scope was too narrow, and needed to include novel business models [96]. Others, however, claimed that product diversification required a more fundamental change in the relative prices of raw materials as well as significant further R&D and development efforts [97].

4.4. In Search for New Cooperative Approaches and Value Chains, 2000–2010

When entering the 21st century, a few of the success factors facilitating the past transition away from fossil fuels had been lost. The role of the research institutes, such as the STFI, was now weaker. In addition, while innovations had for long been developed in close cooperation with institutes, equipment suppliers and consultants, this now occurred to a lesser extent. Often, R&D would simply be outsourced to technology providers such as Valmet and Metso [98]. The level of corporate R&D among Swedish pulp and paper producers was (and has remained) low, typically below one (1) percent of the total turnover [99,100]. Instead, the universities have come to dominate the R&D landscape, in turn resulting in relatively low levels of applied R&D as well as comparatively limited coordination and information sharing among key industrial partners.

Still, at the turn of the century, attempts were made to revitalize the R&D collaboration arenas in the Swedish pulp and paper industry, not least by promoting more applied R&D that could serve as an efficient bridge between basic R&D and commercial application. In the preparatory work for a new energy research endeavor, the so-called "Resource efficient and climate-friendly forest industry" program, Wejding and Wendt [101] argued that such applied R&D ought to be conducted with close cooperation between the researchers (at universities and institutes), the process engineers within the industry, and the relevant equipment suppliers.

> Such an approach ensures that results from basic R&D are exposed, that they are assessed from the perspective of the industry and equipment suppliers, and that investment and operational economic analyses are conducted in a serious manner (Wejding and Wendt [101], 21, authors' translation).

The new R&D program—which, as of August 2020, is still ongoing—has searched for solutions to the pulp and paper industry's challenges in the energy field. The first ten years of the program were characterized by quite a strong focus on black liquor gasification and process integration, i.e., methods for designing integrated production systems, ranging from individual processes to total sites, often with a special emphasis on energy efficiency. The new program also involved R&D on forest-based biorefineries, i.e., in which the entire potential of forest raw materials and byproducts are used to produce a diverse set of products, including transport fuels, chemicals, and bio-based materials alongside the traditional pulp and paper products [102,103].

In 2012, the pulp and paper industry's new energy R&D program was evaluated [104], and this evaluation concluded that the program helped improve the competitiveness of the sector. Interviews with company representatives showed that an important component of the program was that it established an arena for collaboration and information sharing among technicians. Such interactions were, not least, important for facilitating the adoption of energy-efficient equipment in auxiliary systems, e.g., pumps and fans [105,106]. In this way, the program succeeded in revitalizing at least a few components of the old innovation system.

At the same time, other weaknesses in the system remained unattended. Most notably, the Swedish government chose a highly proactive and coordinated strategy in response to the oil crises during the 1970s [15], e.g., engaging several government agencies in the above-mentioned energy program [62]. Even if public R&D expenditures increased during the early 2000s (see also Figure 2), largely due to increased concerns about climate change, clear signs of policy coordination have been less frequent since the turn of the century. Research instead points to a lack of coordination—and even mutual understanding—among government ministries and authorities in relation to the industrial energy transition [107]. This hampered the progress from the pilot and demonstration phase to the commercial adoption phase in the pulp and paper industry since the required policy tools were not in the realm of a single ministry. The absence of far-reaching policy coordination has been particularly negative for the progress of more radical biorefinery concepts, including black liquor gasification, which requires long development periods during which a large number of technological and market-related uncertainties are reduced, effective actor networks emerge and existing institutions are aligned. In fact, the pulp and paper companies' interests in black liquor gasification weakened during the 2000s [104]. These companies have instead become more interested in lignin extraction, which involves fewer changes in the core processes and therefore lower risks [98].

Research shows that often biorefinery development projects have lacked participation from the pulp and paper industry (however, see Peck et al. [108] for some exceptions). The development of novel biorefinery concepts requires new types of challenges and forms of cooperation compared to earlier, thus often spanning across different industries as well as areas of expertise. Ericsson and Nilsson [98] note:

> The strategic competences of the [Swedish pulp and paper industry] in this regard are wood acquisition and wood processing while it does lack the knowledge, infrastructure and distribution channels related to chemicals and transportation fuels. Collaboration across industry sectors and with public agencies is therefore considered necessary for the development of biorefineries (pp. 23–24).

The pulp and paper industry has traditionally, however, relied on single industry platforms; this implies difficulties in establishing effective strategic partnerships with actors along new value chains [109,110]. Instead, the development activities in the biorefinery field increasingly take place in niche organizations and equipment suppliers. This, though, can halt the emergence of promising and valuable chains, since incumbent actors often are the ones who integrate emerging technological trajectories into existing operations.

Finally, the often limited ability of the pulp and paper industry to absorb and translate new knowledge into new business opportunities, and use this to pursue commercial opportunities outside their core business segments, has also contributed to the limited involvement in biorefinery development [107]. The low levels of corporate R&D referred to above can be viewed as an indicator of a relative lack of absorptive capacity. This lack of absorptive capacity may not only be related to potential future markets and customers; it may also relate to procedural knowledge in terms of how the industry interacts and collaborates with different types of actors and shares experiences [111].

5. Discussion

This paper has shown that the sectoral innovation system (SIS) of the Swedish pulp and industry performed well in terms of responding to the soaring energy prices in the 1970s, including the development and diffusion of new energy efficient and fossil-free processes. These results are in line with previous research concluding that the specific contextual and historically shaped conditions of this particular industrial sector in many ways have facilitated the transition to deep emissions reductions, cleaner energy use, and improved energy efficiency [1,15,112,113]. The transition relied on government involvement in industry-wide R&D projects, and intense information sharing among the key actors. New knowledge and energy-efficient processes were advanced jointly and sometimes incrementally through close interactions between the pulp and paper companies, the government authorities and the research institutes.

An important contribution of this paper is its emphasis on the role of industry research institutes. During the 1980s, the STFI played a particularly important role in terms of serving as a bridge between basic energy R&D and industrial application. The academic literature on sustainability transitions has not studied industry research institutes in much detail (see, however, Bergquist and Söderholm [43] and Guan et al. [114]). Our analysis suggests that such institutes could fill important gaps in the innovation systems of process industries. First, in the process industries, technological development largely takes place as a result of the R&D efforts undertaken by equipment suppliers, universities, consultants, and industry research institutes. In this context, the industry institutes often serve as collaborative arenas for all these actors, thus ensuring that basic R&D can be channeled into industry-focused applied R&D and pilot and demonstration projects.

Moreover, through these institutes, which are typically cofunded by the government, industrial companies could also overcome the private disincentives for investments in corporate R&D. One barrier includes the high development costs of technological development in relation to highly uncertain rates-of-return in terms of market opportunities and improved performance [98,115]. The knowledge generated in association with new process technology also tends to diffuse rapidly, which creates difficulties in controlling property rights to any innovations (through patents). Nevertheless, by pooling resources in a joint research institute, industrial companies can considerably decrease costs and risks. This could also make it possible to reach a critical mass of R&D activities aimed at general-purpose technologies (see also [40]).

Previous economics research has noted that some forms of R&D cooperation among industrial companies could result in strategic behavior and even market efficiency (cartelization) [116]. Still, the incentives for such behavior will differ across various sectors, e.g., due to the degree of product differentiation. Notably, in the pulp and paper industry there is typically a relatively high degree of product differentiation with different producers operating in rather closed markets and facing partly different customers [40]. In other words, the risk of cartelization-like behavior should not be that high in this sector.

Our analysis also carries a few important implications for policy. The most basic implication is that the role of policy stretches beyond the funding of basic R&D and concept development. Policy also plays an important role in expanding the scope of the learning processes beyond advancing scientific knowledge and reducing technical risks, and towards promoting both general and proprietary knowledge development such as learning-by-doing (see also [117]). For instance, a mix of government R&D support and cofunding pilot and demonstration plants and applied R&D at industry research institutes can create variation, and permit new inventions to be verified, optimized and up-scaled [29]. Our analysis of the Swedish pulp and paper industry has illustrated how the Swedish government began to give priority to university research during the late 1980s and 1990s, and how this led to reduced R&D being applied, and, in turn, a weakened innovation system. However, universities and industry research institutes are not substitutes for this (see also [118]).

Furthermore, policy also needs to involve measures that strengthen existing actor networks—so-called network management. Specifically, this implies government interventions that initiate new interactions and coalition building, but also attempts to set up goals and visions, as well as propose effective organizational solutions [3]. Our empirical results support the conclusion made by Hansen and Coenen [110] that the important role of the incumbent pulp and paper industry for biorefinery development should make the case for network management a strong one.

> [. . .], regarding the new value chain relations, the analysis suggests that facilitation of contact to downstream actors is very important for the commercialization of biorefinery technologies, [...]. Thus, policy can potentially play an important role in facilitating network formation by creating arenas for interaction between pulp and paper firms and potential downstream actors (p. 509).

In other words, given the new challenges for the pulp and paper industry, government policy in the context of sustainable technological development must increasingly address the character, the performance and the outcome of actor networks.

Finally, while this paper supports previous research emphasizing that innovation policy needs to build on a wide mix of various instruments [119], it also illustrates that relatively high-performing innovation systems can lose momentum due to largely external factors, such as structural change in the industrial sector and altered political preferences. For this reason, an important component of innovation policy is to conduct continuous follow-ups on the strengths and weakness of existing innovation systems.

6. Conclusions

This article provides an innovation system perspective of the development of energy efficient and clean process technologies in the Swedish pulp and paper industry over a four decade-long period. The analysis elaborated on the importance of knowledge development, actor networks, and institutions (including policy intervention) for developing and diffusing energy-efficient and clean technology in this sector. Moreover, significant changes in the sectoral innovation system were shown to have influenced the relevant R&D and demonstration activities, not least through a weakening of research institutes, such as the STFI, which engaged in both basic and applied R&D but also assisted in stimulating knowledge transfer in industry.

Overall, the results illustrate the importance of well-functioning sectoral innovation systems for successful technological development and diffusion processes. Industry-wide R&D activities, trust-based state–industry relationships, and intense information sharing, are vital prerequisites for successful industrial energy transitions. One important implication is that the role of policy stretches beyond the funding of basic R&D—it also involves instruments that strengthen actor networks, build competence, and support the applied industry research institutes, which can help provide bridges between basic knowledge generation and concept development (at universities) on the one hand, and industrial applications on the other. Government interventions to promote new actor networks are particularly important for current attempts to progress different biorefinery technologies.

The analysis in this article also indicates a number of interesting avenues for future research. Even though the paper has illustrated that significant improvements in energy use and efficiency took place from the 1970s and onwards, there exist important barriers to further—and, not least, provide more radical—innovation in the pulp and paper production processes, e.g., high capital intensity and use. This opens up for future research work on how efficient green innovation systems can be established that promote the development of zero-carbon production technologies in capital-intensive process industries. As noted above, the important role of industry research institutes is to be collaborative arenas linking basic knowledge generation (at the universities) on the one hand, and promote commercial adoption on the other. Moreover, the pulp and paper industry's increased focus on product and not only process innovation implies yet other challenges in the form of the need for increased collaboration with new types of actors, such as companies in other industry sectors, as well as an increased ability to absorb new knowledge and pursue commercial opportunities outside the core business segments.

Author Contributions: Conceptualization, K.S. and P.S.; methodology, K.S. and P.S.; formal analysis, K.S. and P.S.; data collection, K.S.; writing—original draft preparation, K.S. and P.S.; writing—review and editing, K.S. and P.S.; funding acquisition, K.S. and P.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research undertaken in preparation for this article was funded by the Swedish Energy Agency and the Swedish Research Council Formas.

Acknowledgments: Valuable comments on earlier drafts of this article from Karin Ericsson, Lund University, are gratefully acknowledged. Any remaining errors, however, reside solely with the authors.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Bergquist, A.K.; Söderholm, K.; Kinneryd, H.; Lindmark, M.; Söderholm, P. Command-and-control revisited: Environmental compliance and technological change in Swedish industry. *Ecol. Econ.* **2013**, *85*, 6–19. [CrossRef]
2. Sandén, B.A.; Azar, C. Near-term technology policy for long-term climate targets. Economy-wide versus technology specific approaches. *Energy Policy* **2005**, *33*, 1557–1576. [CrossRef]
3. Söderholm, P.; Hellsmark, H.; Frishammar, J.; Hansson, J.; Mossberg, J.; Sandström, A. Technological development for sustainability: The role of network management in the innovation policy mix. *Technol. Forecast. Soc. Chang.* **2019**, *138*, 309–323. [CrossRef]
4. Wesseling, J.H.; Lechtenböhmer, S.; Åhman, M.; Nilsson, L.J.; Worell, E.; Coenen, L. The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renew. Sustain. Energy Rev.* **2017**, *79*, 1303–1313. [CrossRef]
5. Bento, N.; Wilson, C. Measuring the duration of formative phases for energy technologies. *Environ. Innov. Soc. Transit.* **2016**, *21*, 95–112. [CrossRef]
6. Thollander, P.; Ottosson, M. An energy efficient Swedish pulp and paper industry—Exploring barriers to and driving forces for cost-effective energy efficiency investments. *Energy Effic.* **2007**, *1*, 21–34. [CrossRef]
7. Schleich, J. Barriers to energy efficiency: A comparison across the German commercial and services sector. *Ecol. Econ.* **2009**, *68*, 2150–2159. [CrossRef]
8. Wolf, A.; Petersson, K. Industrial Symbiosis in the Swedish Forest Industry. *Prog. Ind. Ecol. Int. J.* **2007**, *4*, 348–362. [CrossRef]
9. Åhman, M.; Nilsson, L.J.; Johansson, B. Global climate policy and deep decarbonization of energy-intensive industries. *Clim. Policy* **2017**, *17*, 634–649. [CrossRef]
10. Amjadi, G.; Lundgren, T.; Persson, L. The rebound effect in Swedish heavy industry. *Energy Econ.* **2018**, *71*, 140–148. [CrossRef]
11. Henriksson, E.; Söderholm, P.; Wårell, L. Industrial electricity demand and energy efficiency policy: The role of price changes and private R&D in the Swedish pulp and paper industry. *Energy Policy* **2012**, *47*, 437–446. [CrossRef]
12. Lindmark, M.; Bergquist, A.-K.; Andersson, L.-F. Energy transition, carbon dioxide reduction and output growth in the Swedish pulp and paper industry: 1973–2006. *Energy Policy* **2011**, *39*, 5449–5456. [CrossRef]

13. Stenqvist, C. Trends in energy performance of the Swedish pulp and paper industry: 1984–2011. *Energy Effic.* **2015**, *8*, 1–17. [CrossRef]
14. Zhang, S.; Lundgren, T.; Zhou, W. Energy efficiency in Swedish industry: A firm-level data envelopment analysis. *Energy Econ.* **2016**, *55*, 43–51. [CrossRef]
15. Bergquist, A.K.; Söderholm, K. Sustainable energy transition: The case of the Swedish pulp and paper industry 1973–1990. *Energy Effic.* **2016**, *9*, 1179–1192. [CrossRef]
16. Ottosson, M. Opposition and Adjustment to Industrial Greening—The Swedish Forest Industry's (Re)actions Regarding Energy Transition 1989–2009. Ph.D. Thesis, Linköping Studies in Arts and Science No. 526. Linköping University, Linköping, Sweden, 2011.
17. Royal Swedish Academy of Engineering Sciences. *Energieffektivisering av Sveriges Industri. HINDER och möjlIgheter att nå en Halverad Energianvändning Till 2050*; IVA: Stockholm, Sweden, 2013.
18. Swedish Energy Agency. *Effektiv Energianvändning. En Analys av Utvecklingen 1970–1998*; Statens Energimyndighet: Eskilstuna, Sweden, 2000.
19. Fracoro, G.; Vakkilainen, E.; Hamaguchi, M.; Nelson, S.; de Souza, M. Energy efficiency in the Brazilian pulp and paper industry. *Energies* **2012**, *5*, 3550–3572. [CrossRef]
20. Flanagan, K.; Uyarra, E.; Laranja, M. Reconceptualising the 'policy mix' for innovation. *Res. Policy* **2011**, *40*, 702–713. [CrossRef]
21. Musiolik, J.; Markard, J. Creating and shaping innovation systems: Formal networks in the innovation system for stationary fuel cells in Germany. *Energy Policy* **2011**, *39*, 1909–1922. [CrossRef]
22. Hoppmann, J.; Huenteler, J.; Girod, B. Compulsive policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power. *Res. Policy* **2014**, *43*, 1422–1441. [CrossRef]
23. Malerba, F. Sectoral systems of innovation and production. *Res. Policy* **2002**, *31*, 247–264. [CrossRef]
24. Nelson, R.; Winter, S. *An Evolutionary Theory of Economic Change*; Belknapp Press: Cambridge, MA, USA, 1982.
25. Malerba, F. Sectoral systems of innovation: A framework for linking innovation to the knowledge base, structure and dynamics of sectors. *Econ. Innov. New Technol.* **2005**, *14*, 63–82. [CrossRef]
26. Edquist, C. *Systems of Innovation*; Frances Pinter: London, UK, 1997.
27. Nelson, R. *National Innovation Systems: A Comparative Analysis*; Oxford University Press: New York, NY, USA, 1993.
28. Teubal, M.; Yinnon, T.; Zuscovitch, E. Networks and market creation. *Res. Policy* **1991**, *20*, 381–392. [CrossRef]
29. Hellsmark, H.; Frishammar, J.; Söderholm, P.; Ylinenpää, H. The role of pilot and demonstration plants in technology development and innovation policy. *Res. Policy* **2016**, *45*, 1743–1761. [CrossRef]
30. Rosenberg, N. *Inside the Black Box: Technology and Economics*; Cambridge University Press: New York, NY, USA, 1983.
31. Belderbos, R.; Carree, M.; Lokshin, B. Cooperative R&D and firm performance. *Res. Policy* **2004**, *33*, 1477–1492. [CrossRef]
32. Cohen, W.M.; Levinthal, D.A. Absorptive capacity: A new perspective on learning and innovation. *Adm. Sci. Q.* **1990**, *35*, 128–152. [CrossRef]
33. Liu, Z.; Jongsma, M.A.; Huang, C.; Dons, J.J.M.; Omta, S.W.F. The sectoral innovation system of the Dutch vegetable breeding industry. *NJAS Wagening. J. Life Sci.* **2015**, *74–75*, 27–39. [CrossRef]
34. Laestadius, S. Technology level, knowledge formation, and industrial competence in paper manufacturing. In *Microfoundation of Economic Growth: A Schumpeterian Perspective*; Eliasson, G., Green, C., McCann, C.R., Eds.; University of Michigan Press: Ann Arbor, MI, USA, 1998.
35. Weber, K.M.; Rohracher, H. Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. *Res. Policy* **2012**, *41*, 1037–1047. [CrossRef]
36. Rogge, K.S.; Reichardt, K. Policy mixes for sustainability transitions: An extended concept and framework for analysis. *Res. Policy* **2016**, *45*, 1620–1635. [CrossRef]
37. Meadowcroft, J. Engaging with the politics of sustainability transitions. *Environ. Innov. Soc. Transit.* **2011**, *1*, 70–75. [CrossRef]
38. Nilsson, L.J.; Johansson, B.; Åstrand, K.; Ericsson, K.; Svenningsson, P.; Börjesson, P.; Neij, L. Seeing the wood for the trees: 25 years of renewable energy policy in Sweden. *Energy Sustain. Dev.* **2004**, *8*, 67–81. [CrossRef]
39. Eriksson, L. *STFIs Öden och Äventyr 1942–2010: Fakta-Minnen-Reflexioner*; Spearhead Production: Stockholm, Sweden, 2010.

40. Marklund, G. *Institutions and Appropriation in Swedish Technology Policy*; Graphic Systems: Stockholm, Sweden, 1994.
41. Wittrock, B.; Lindström, S. *De Stora Programmens Tid. Forskning och Energi i Svensk Politik*; Akademilitteratur: Stockholm, Sweden, 1984.
42. Swedish Steam Generator Association. *Energy Conservation in the Chemical Process Industry: Examples from the Pulp and Paper Industry*; Ångpanneföreningen (ÅF): Stockholm, Sweden, 1974.
43. Bergquist, A.K.; Söderholm, K. Green innovation systems in Swedish industry 1960–1989. *Bus. Hist. Rev.* **2011**, *85*, 677–698. [CrossRef]
44. New techniques in environmental protection and energy saving go hand in hand. *Sven. Papp.* **1985**, *7*.
45. Pulp and Paper Research Foundation. *Minutes from Board Meeting (Protocol no. 8, 23 January, 1973)*; The Stockholm Centre for Business History Archive: Stockholm, Sweden, 1973.
46. Om FoU på energiområdet. *Sven. Papp.* **1975**, *9*.
47. Wiberg, R. *Energiförbrukning i Massa-Och Pappersindustrin 1973*; Swedish Pulp and Paper Mill Association (SCPF): Stockholm, Sweden, 1974.
48. Viktiga referensverk för energianalyser och energibalanser. *Sven. Papp.* **1984**, *14*.
49. Jönsson, S.-E.; Nygaard, J.; Wiberg, R. *Modeller för Energihushållning i Massa- och Papperstillverkning. Sulfatfabrik för Blekt Avsalumassa*; Swedish Steam Generator Association (ÅF): Stockholm, Sweden, 1976.
50. Jönsson, S.-E.; Nygaard, J.; Wiberg, R. *Modeller för Energihushållning i Massa-Och Papperstillverkning. Kraftlinerbruk*; Swedish Steam Generator Association (ÅF): Stockholm, Sweden, 1976.
51. Jönsson, S.-E.; Nygaard, J.; Wiberg, R. *Modeller för Energihushållning i Massa-Och Papperstillverkning. Mjukpappersbruk*; Swedish Steam Generator Association (ÅF): Stockholm, Sweden, 1977.
52. Jönsson, S.-E.; Nygaard, J.; Wiberg, R. *Modeller för Energihushållning i Massa-Och Papperstillverkning. Tidningspappersbruk*; Swedish Steam Generator Association (ÅF): Stockholm, Sweden, 1977.
53. Regestad, S. Skogsindustriella forsknings-och utvecklingsprojekt inom energiområdet. *Sven. Papp.* **1977**, *14*.
54. Söderholm, K.; Bergquist, A.-K. Firm collaboration and environmental adaptation: The case of the Swedish pulp and paper industry, 1900–1990. *Scand. Econ. Hist. Rev.* **2012**, *60*, 183–211. [CrossRef]
55. Sundblad, E. Skogsindustrin och energifrågorna. *Sven. Papp.* **1977**, *9*.
56. Robertsson, O. Energibesparande åtgärder i sulfatfabriker. *Sven. Papp.* **1975**, *1*.
57. Wohlfahrt, G. Energihushållningen i massa-och pappersindustrin. Om pågående utredningsverksamhet på branschnivå. *Sven. Papp.* **1977**, *1*.
58. Lundqvist, L.J. *Sweden and Ecological Governance: Straddling the Fence*; Manchester University Press: Manchester, UK, 2004.
59. Sörlin, S. *En ny Institutssektor. En Analys av Industriforskningsinstitutens Villkor Och Framtid ur ett Närings-Och Innovationspolitiskt Perspektiv*; Ministry of Enterprise, Energy and Communications: Stockholm, Sweden, 2006.
60. Smith, M. *The US Paper Industry and Sustainable Production. An Argument for Restructuring*; MIT Press: Cambridge, MA, USA, 1997.
61. Porter, M.E.; Sölvell, Ö.; Zander, I. *Advantage Sweden*, 2nd ed.; Palgrave Macmillan: London, UK, 1992.
62. Government Bill 1975:30. *Regeringens Proposition om Energihushållning m.m.*; Swedish Government: Stockholm, Sweden, 1975.
63. Haegermark, H. Priorities of energy research in Sweden. In *Building Sustainable Energy Systems. Swedish Experiences*; Silveira, S., Ed.; Swedish National Energy Administration: Eskilstuna, Sweden, 2001; pp. 163–195.
64. Swedish Industry Agency (SIND). *Statens Industriverk. Series of Publications 1983:2*; Allmänna Förlaget: Stockholm, Sweden, 1978.
65. International Energy Agency. *RD&D Budget. IEA Energy Technology RD&D Statistics (Database)*; OECD: Paris, France, 2020.
66. Rydin, B. Energianvändningen i industrin. *Sven. Papp.* **1980**, *1*.
67. Slaget om energin avgör skogsindustrins framtid. *Sven. Papp.* **1982**, *5*.
68. Swedish Industry Agency (SIND). *PoD-Rapportering: Energi. Sammanställning av Slutrapporter Från Genomförda Prototyp-Och Demonstrationsanläggningar inom Energiområdet*; Allmänna Förlaget: Stockholm, Sweden, 1986.
69. Ekstedt, E. *Humankapital i Brytningstid. Kunskapsuppbyggnad och Förnyelse för Företag*; Allmänna Förlaget: Stockholm, 1988.
70. Richter, J. *The History of the Kamyr Continous Cooking*; Industrihistorisk Skriftserie No. 7; Swedish Pulp and Paper Mill Association (SCPF): Stockholm, Sweden, 1981.

71. Söderholm, K.; Bergquist, A.K. Growing green and competitive: A case study of a Swedish pulp mill. *Sustainability* **2013**, *5*, 1789–1805. [CrossRef]
72. Nytt processtyrsystem för slipverk ger halverad energiförbrukning. *Sven. Papp.* **1988**, *3*.
73. Stockman, L. Samarbete—En styrka i teknisk utveckling. *Sven. Papp.* **1985**, *5*.
74. Sodapannan—Inte längre en flaskhals. *Sven. Papp.* **1986**, *4*.
75. Processtyrning och mätteknik ger svensk skogsindustri konkurrensfördel. *Sven. Papp.* **1987**, *9*.
76. "Think small" mottot för ny informations-, mät-och styrteknik. *Sven. Papp.* **1996**, *11*.
77. Croon, I. Samarbete—viktigt konkurrensmedel även för de nystora. *Sven. Papp.* **1987**, *4*.
78. Pettersson, I. Handslaget—Svensk Industriell Forskningspolitik 1940–1980. Ph.D. Dissertation, Royal Institute of Technology, Stockholm, Sweden, 2012.
79. Government Bill 1992/93:170. *Forskning för Kunskap Och Framsteg*; Swedish Government: Stockholm, Sweden, 1993.
80. Lindvall, J.; Sebring, J. Policy reform and the decline of corporatism in Sweden. *West Eur. Politics* **2005**, *28*, 1057–1074. [CrossRef]
81. Kronsell, A.; Khan, J.; Hildingsson, R. Actor relations in climate policy-making: Governing decarbonisation in a corporatist green state. *Environ. Policy Gov.* **2019**, *29*, 399–408. [CrossRef]
82. Brunner, H. Industristyrd forskning är effektiv. *Bergsmannen* **1992**, *1*, 35.
83. Järvinen, J.; Ojala, J.; Melander, A.; Lamberg, J.A. The evolution of the pulp and paper industries in Finland, Sweden and Norway 1800–2005. In *The Evolution of Global Paper Industry, 1800–2050. A Comparative Analysis*; Lamberg, J.A., Ojala, J., Peltoniemi, M., Särkkä, T., Eds.; Springer: Dordrecht, The Netherlands, 2012; pp. 19–48.
84. Kretsloppsanpassa massafabrik—Nytt MISTRA-program. *Sven. Papp.* **1996**, *12*.
85. KAM-programmet engagerar många aktörer. *Sven. Papp.* **1999**, *2*.
86. Massaforskning ger energi. *Sven. Papp.* **2000**, *4*.
87. Pumpa rätt, spara el. *Sven. Papp.* **1991**, *5*.
88. Dags att generera mer mottryckskraft. *Sven. Papp.* **1993**, *4*.
89. Ericsson, K.; Nilsson, L.J.; Nilsson, M. New energy strategies in the Swedish pulp and paper industry—The role of national and EU climate and energy policies. *Energy Policy* **2011**, *39*, 1439–1449. [CrossRef]
90. Kretsloppsanpassning i massabruket—Var står man. *Sven. Papp.* **1998**, *1*.
91. Svartlutsförgasning ny flexibel teknik som kan ersätta sodapannan. *Sven. Papp.* **1995**, *10*.
92. Svartlutsförgasning och impulstorkning ska alstra och spara energi. *Sven. Papp.* **1997**, *5*.
93. Karltorp, K.; Sandén, B.A. Explaining regime destabilization in the pulp and paper industry. *Environ. Innov. Soc. Transit.* **2012**, *2*, 66–81. [CrossRef]
94. KAMs arbete kan snart förändra massaindustrin. *Sven. Papp.* **2003**, *3*.
95. Nätverk lyfter lignin. *Sven. Papp.* **2004**, *10*.
96. Kretsloppsanpassning i massabruket—Till viken nytta? *Sven. Papp.* **1998**, *5*.
97. Forsström, A. Biomassaindustrin är framtiden. *Sven. Papp.* **1994**, *5*.
98. Ericsson, K.; Nilsson, L.J. *Climate Innovations in the Paper Industry: Prospects for Decarbonisation*; IMES/EESS Report No. 110; Department of Technology and Society, Lund University: Lund, Sweden, 2019.
99. Kivimaa, P.; Kautto, P.; Hildén, M.; Oksa, J. *What Drives Environmental Innovations in the Nordic Pulp and Paper Industry? Green Markets and Cleaner Technologies (GMCT)*; Nordic Council of Ministers: Copenhagen, Denmark, 2008.
100. Novotny, M.; Laestadius, S. Beyond papermaking: Technology and market shifts for wood-based biomass industries—Management implications for large-scale industries. *Technol. Anal. Strateg. Manag.* **2014**, *26*, 875–891. [CrossRef]
101. Wejding, S.; Wendt, C.-H. *Polymerkemi Och Polymerfysik (PKF): Utvärdering av Industriell Relevans Och Effekt 1990–1996*; Report 1997:14; NUTEK: Stockholm, Sweden, 1997.
102. Söderholm, P.; Lundmark, R. The development of forest-based biorefineries: Implications for market behavior and policy. *For. Prod. J.* **2009**, *59*, 6–16.
103. Pandey, A. *Biofuels: Alternative Feedstocks and Conversion Processes*; Academic Press: Oxford, UK, 2011.
104. Åström, T.; Swenning, A.-K.; Håkansson, A.; Jansson, T. *Utvärdering av Värmeforsks Skogsindustriella Program*; Technopolis Group: Stockholm, Sweden, 2012.
105. Samarbete skall minska energiförbrukningen. *Sven. Papp.* **2000**, *9*.

106. Hannus, M. Växande marknad för energieffektiv teknik. *Sven. Papp.* **2007**, *10*.
107. Hellsmark, H.; Mossberg, J.; Söderholm, P.; Frishammar, J. Innovation system strengths and weaknesses in progressing sustainable technology: The case of Swedish biorefinery development. *J. Clean. Prod.* **2016**, *131*, 702–715. [CrossRef]
108. Peck, P.; Grönkvist, S.; Hansson, J.; Lönnqvist, T.; Voytenko, Y. *Systemic Constraints and Drivers for Production of Forest-Derived Transport Biofuels in Sweden. Part A: Report and Part B: Case Studies*; f3 reports 2016:9a and 2016:9b; The Swedish Knowledge Centre for Renewable Transportation Fuels: Gothenburg, Sweden, 2016.
109. Bauer, F.; Hansen, T.; Hellsmark, H. Innovation in the bioeconomy—Dynamics of biorefinery innovation networks. *Technol. Anal. Strateg. Manag.* **2018**, *30*, 935–947. [CrossRef]
110. Hansen, T.; Coenen, L. Unpacking resource mobilisation by incumbents for biorefineries: The role of micro-level factors for technological innovation system weaknesses. *Technol. Anal. Strateg. Manag.* **2017**, *29*, 500–513. [CrossRef]
111. Frishammar, J.; Söderholm, P.; Hellsmark, H.; Mossberg, J. A knowledge-based perspective on system weaknesses in technological innovation systems. *Sci. Public Policy* **2019**, *46*, 55–70. [CrossRef]
112. Reinstaller, A. Technological transition to chlorine free pulp bleaching technologies: Lessons for transition policies. *J. Clean. Prod.* **2008**, *16*, 133–147. [CrossRef]
113. Söderholm, K.; Bergquist, A.-K.; Söderholm, P. The transition to chlorine free pulp revisited: Nordic heterogeneity in environmental regulation and R&D collaboration. *J. Clean. Prod.* **2017**, *165*, 1328–1339. [CrossRef]
114. Guan, J.C.; Yam, R.C.M.; Mok, C.K. Collaboration between industry and research institutes/universities on industrial innovation in Beijing, China. *Technol. Anal. Strateg. Manag.* **2005**, *17*, 339–353. [CrossRef]
115. Lehmann, P.; Söderholm, P. Can technology-specific deployment policies be cost-effective? The case of renewable energy support schemes. *Environ. Resour. Econ.* **2018**, *71*, 475–505. [CrossRef]
116. Chiou, J.-R.; Hu, J.-L. Environmental research joint ventures under emission taxes. *Environ. Resour. Econ.* **2001**, *20*, 129–146. [CrossRef]
117. Edler, J.; Cunningham, P.; Gök, A.; Shapira, P. *Impacts of Innovation Policy: Synthesis and Conclusion*; Nesta Working Paper 13/21; Nesta: London, UK, 2013.
118. Arnold, T.; Brown, N.; Eriksson, A.; Jansson, T.; Muscio, A.; Nählinder, J.; Zaman, R. *The Role of Industrial Research Institutes in the National Innovation System*; VA 2007:12; Swedish Governmental Agency for Innovation Systems (Vinnova): Stockholm, Sweden, 2007.
119. Borrás, S.; Edquist, C. The choice of innovation policy instruments. *Technol. Forecast. Soc. Chang.* **2013**, *80*, 1513–1522. [CrossRef]