Governing Technological Diffusion to Address Climate Change: Transformations in the Nuclear and Bioenergy sectors in Sweden, Brazil, and the United States

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Introduction

If human societies are to address climate change by reducing greenhouse gas emissions, they must better understand the pathways by which transformative technologies become significant components of mainstream energy systems. Transformational change in the world's energy system, as well as associated systems such as agriculture and land use, will be required to address climate change (see, for example, Clarke, Weyant, and Edmonds 2008; Clarke, Weyant, and Birky 2006; Hultman, Koomey, and Kammen 2007). Scenarios for stabilization developed through the U.S. Climate Change Science Program (Clarke et al. 2007) show that energy emissions from freely emitting fossil fuels must eventually approach zero in order to stabilize atmospheric CO_2 concentrations. Current scenarios suggest that this stabilization will require the accelerated and widespread global deployment of a combination of non-emitting and low-carbon energy technologies.

Technological transformation is the core of long term reductions in energy-related emissions, and many controversies surrounding how to structure climate change mitigation and adaptation policies– including financing, what counts as action, and how to measure progress against uncertain goals – are based on differing assumptions about the potential and likely pathways for technological change (Prins et al. 2010). The central questions therefore revolve around the scope of policy to influence or accelerate the diffusion of climate-change-related technology (Holdren 2006). Arguments for pricing emissions correctly are unfortunately insufficient in a world where markets are at best imperfect and equitable well-being is as much a goal as efficiency (Hultman et al. In Press), Therefore, while it is undoubtedly essential to understand the market forces that influence technology development and deployment—and to nurture our capability to model the short-term macroeconomic impact of specific carbon and energy policies, understanding longer-term, large-scale changes in the energy system requires a broader understanding of the relative influence institutional, behavioral, and social factors. For example, changes can be understood to stem from government regulation and policy, differences in firm expertise and infrastructure, international and national needs for security, innovation networks, or leadership. Other factors sometimes mentioned in the literature include the availability of technical expertise, risk-taking behavior in partners and suppliers, co-benefits such as employment in declining sectors or increased national standing, the origin and method of capital infusion, an evolving or permissive regulatory structure, development of diversified markets, standardization of parts and systems, and public acceptance.

The case can inevitably be made that each of these is important in specific circumstances, and influence of such factors have been studied disparately in the literature (Montalvo 2008). Nevertheless, a question remains as to whether any of these non-economic factors is highly influential (or even determinative) across technologies or country situations. This paper presents an interview-based comparative case approach to investigating systematically these the *relative importance* of these non-economic factors influencing technological change *across technology and country contexts*. We identified two low-carbon energy sectors (bioenergy and civilian nuclear power) that witnessed dramatic changes over the past fifty years in the energy portfolio of three countries: Sweden, Brazil, and the United States. We set out to identify which of many possible non-economic factors were seen by sector participants as being determinative or highly influential in the trajectory of that technology in their country context. In this paper, we present findings from 41 interviews across four cases: Nuclear in Sweden/US, and Bioenergy in Sweden/Brazil.

Background

Research on the characteristics of technological transformation has drawn on constructs such as the classic Schumpeterian creative destruction theory (Schumpeter 1934[1974]), long-wave cycles of change, the S-shaped learning curve (beginning with Wright 1936), and the S-shaped diffusion curve (starting with Gabriel Tarde's work in 1903). Case studies such as Hughes' (1985) history of electrification in the United States, Britain, and Germany; or Dobbin's (1994) study of railway introduction and expansion in the United States and France document these large shifts in technological systems (see Rip and Kemp 1998 for a review).

Yet these descriptive studies are of limited prospective help in planning for the kind of technological transformations needed to mitigate climate change emissions in the energy sector. For instance, the S-shaped diffusion curve has been validated in many studies of technological change, but it merely describes the phenomenon by which first a few, then many, then a final few adopt a given technology. As Grübler (Grübler 1997) and others have pointed out, the rate and total time of change cannot be specified prospectively; neither does the curve explain *why* diffusion is taking place. Schumpeter's entrepreneur spearheads new "combinations" that drive technological change, but we do not know why one entrepreneur succeeds and another fails.

More revealing are studies of successful entrepreneurs, such as Thomas Edison, who was able not only to invent but also to find financial backers, persuade governments to set up enabling policy environments, and attract a host of secondary inventors and suppliers who provided continuous improvements (see, e.g., Hughes 1985, Stokes 1997). However, the individual case study as an historical analysis, while demonstrating contingency and complexity, often makes no attempt to generalize or to provide prospective guidance. Moreover, the principal role allotted to the inventor-as-hero obscures driving elements that may be provided in other ways in other situations, such as transformations where there is no dominant actor.

Often associated or conflated with research on technological diffusion are studies of the contribution of R&D to technological innovation and on the sources of innovation generally. Beginning with Vannevar Bush's conviction that the scientific enterprise was a vast storehouse from which endless technological innovations could flow (Bush 1945), this line of research has connected scientific research with U.S. world leadership in innovation, rising GDP, and military dominance. This in turn has led to examining the factors that foster innovation in organizations (see, e.g., Altschuller 1999, Burgelman et al. 1996, Drucker 1993, Hamel 2000, Light 1998).

The immense challenge of climate change has prompted calls for emissions mitigation to be treated as a new "Manhattan Project" or "Apollo Project." However, the analogy to these past, successful large technology projects is not necessarily illuminating. As Prins and Rayner (Prins and Rayner 2007) have pointed out, these focused and heroic projects were able to be successful because they had clear goals and end points; they were, in the authors' words, "tame" problems. Climate change, in contrast, is a "wicked" problem, that is, a problem in which lack of understanding is endemic because so many open-ended systems are involved.

Many literatures inform our understanding of R&D and other sources of innovation but they tell us little about how the diffusion process begins, accelerates, and succeeds or fails. More specialized literatures such as the Social History of Technology, Science and Technology Studies, the Social Construction of Technology, and Actor-Network Theory, while also focusing on case studies, also have begun to develop theories about technology diffusion, many of them related to different dimensions of governance. Latour's (1984[1987]) well-known study about the diffusion of Pasteur's ideas demonstrates that creating an innovation is just the beginning of the process. Pasteur then engaged in extensive effort of creating "order at all points"; he "did not just send results out from his lab; he engaged in a prolonged program to convince farmers, vintners, hygienists, hospitals, and so forth, that he was acting in their interests, and that they ought to incorporate elements of his laboratory regime into their ways of life" (Jasanoff and Wynne 1998). Similarly, Hughes' study of electrification includes lengthy descriptions of persuasion and institution-building. Callon's (1997) actor-network examination of the failure of the electric car in France demonstrates that government policy, technical and manufacturing expertise, and resources can be stymied when research does not produced expected breakthroughs.

Methods

We sought to establish the primary factors influencing significant energy technology transformation across country and technology contexts. Our methods entailed selecting cases, conducting interviews and with key experts in each case context, and analyzing interview data both qualitatively and quantitatively. We chose two technology classes—bioenergy and nuclear power—across three countries: the United States, Sweden, and Brazil. Collectively, these countries exhibit similarities in their respective patterns of energy technology (non) adoption, and thus offer a useful and valid sample for analysis and generalization of results.

Ethanol has attracted renewed attention as a potentially renewable transportation fuel, although controversy surrounds its net environmental impact and energy balance (Pimentel and Patzek, 2005; Shapouri et al., 2002; Runge and Senauer, 2007) (Farrell et al. 2006). Each of the country cases illustrates efforts to adopt and diffuse ethanol as a major element of the transportation fuel mix and each focuses on factors identified in the literature as necessary elements of successful technology diffusion (see Malone 2004 and Dooley et al. 2006). In studies of ethanol adoption in Brazil, Sweden, and the United States and of the use of biomass from forest wastes for heat and power production in Sweden, we hypothesized several important variables, including policies giving preferential treatment to bioenergy-related technologies, government-industry relations, the role of technological innovation, relevant domestic natural resources and feedstocks, and perceptions of technology risk on the part of key stakeholders.

While these and many other variables are influential in the successful adoption and diffusion of new energy technologies, the bioenergy cases discussed here offer particularly valuable studies of the interplay of technological and natural resource variables. The availability of sufficient domestic supplies of high quality (i.e., energy dense and economically convertible) feedstocks for ethanol production and the state-of-the-art of conversion technologies may be more decisive than other variables in determining success or failure.

Rising and volatile petroleum prices, geopolitical conflicts in fossil-fuel rich regions, increasing energy demand from emerging economies, and climate change have all contributed to a resurgence of interest in nuclear power based on its potential to address energy security without emitting carbon dioxide or regional pollutants (Sailor et al. 2000; Rothwell 2006; Bokenkamp et al. 2005; Rothwell 2000; Reedman, Graham, and Coombes 2006). Past experience with such large-scale technological ventures highlights linked policy, cultural, and economic challenges, some of which may not be amenable to technological solution (La Porte 1994). As a source of electricity that could, from a technical standpoint, provide a substitute for large, centrally sited, baseload coal-fired power, nuclear power can be a significant possible contributor to reducing greenhouse gas emissions. Nevertheless, varied experiences with nuclear power underscore the relatively minor role that technical feasibility and technological elegance has within the wider social matrix. Interrelated problems of spiraling costs, government policy, and public opposition led to a virtual moratorium on the construction of new nuclear technology that is only now lifting.

Re-examining this telling experience in nuclear deployment provides a sound comparison to the ethanol case. Nuclear power experienced a contentious history and cost escalation in the United States (Koomey and Hultman 2007) which led to a long period of uncertainty in the industry (Hultman and Koomey 2007) Sweden has had a mixed experience varied with nuclear power. After a long period of public acceptance of nuclear power, in the 1990s voters elected to phase out all nuclear power by 2000; this policy was then reversed, and reversed again, and now Sweden retains a commitment to become nuclear-free. Brazil provides an interesting foil to Sweden: like Sweden, it began developing a domestic nuclear industry and continues to run one commercial reactor, but unlike Sweden it did not develop a large-scale commercial nuclear power industry and therefore may offer some insights into additional non-economic barriers to the adoption of this technology.

Together, the two technologies across three countries comprise six research comparisons (Brazil-Nuclear, Brazil-Bioenergy, Sweden-Nuclear, Sweden-Bioenergy, U.S.-Nuclear, U.S.-Bioenergy). For each comparison, the team selected 12-20 interviewees from four general categories: government officials and policymakers, industry managers, researchers, and market/industry analysts. The team conducted semi-structured interviews that began with an open-ended question asking what factors the interviewee considered important in the development of nuclear power or bioenergy in his or her country. Then interviewees were presented with a set of nine cards, each of which described a factor derived from the literature on technological transformation. These factors are shown in **Table 1** and also described more fully in Appendix A. Participants were asked to assign weights to the factors they consider most important in the diffusion process for the technology. In some interviews, interviewees were asked to sort the cards into three categories: determinative (i.e., absolutely essential to the diffusion of the technology), important (but not determinative), and not important. For this paper, we report on the results from a collection of 41 interviews[1] conducted in Sweden, Brazil, and the United States from March 2009 through September 2010.

Results: Narrative Responses

In their narrative answers to the open-ended question, "What factors do you view as most important in the development of [Nuclear Power / Bioenergy] in [Brazil/Sweden/United States]?", interviewees in both Sweden and Brazil told similar stories about how nuclear and biofuels technologies became major players (e.g., nuclear and biomass in Sweden, ethanol in Brazil) or negligible/minor contributors to the energy sector (biofuels in Sweden, nuclear in Brazil). In the United States, the narratives diverge somewhat – not in the factors themselves, considered as a set, but in the emphases and details given by individual interviewees. We present four narratives in this paper: Biomass in Sweden/Ethanol in Brazil and Nuclear in Sweden and the United States.

a. Brazilian Ethanol: Narrative Responses

Oil Crisis & Proalcool Program

At the time of the 1973 Oil Crisis, approximately 80% of Brazil's oil was imported. When oil prices increased, the import bill increased from 500 million to 4 billion dollars, which drastically worsened Brazil's trade balance. The 1975 Proalcool Program, which was a revision of an earlier ethanol program, was seen as a solution to both energy and economic problems, gave new economic life to the floundering domestic sugarcane industry, and addressed regional imbalances with movement to the interior and rural development.

The technology was available; sugarcane mills were upgraded to be able to produce ethanol as some distilleries already could produce sugar and ethanol. Further, since the 1931 blend mandate, car engines could also run on ethanol up to certain levels. Institutional support and memory came from the Institute of Sugar and Alcohol (IAA), which had been created to control mill quotas for sugar and ethanol, as well as quantities of exports and prices. Complementing mill adaptation, the IAA also facilitated partnerships between the private sugar plantations, the World Bank, and mill equipment manufacturers, like Dedini, which were responsible for the boom of over 100 new mills in the1970s. However, the firm structure or corporate culture of the older sugarcane mills was not conducive to the expansion of ethanol. Many of the cane plantations were traditionally run by families and were not used to the new technologies, management, or labor relations.

[1] Of these, 36 were included in the data analysis below, and 5 were considered "context interviews" because participants either were not prompted or did not give complete answers to the factor questions in the interview protocol.

Factor	Elements
Decisionmaking characteristics of firm	Firm's willingness to take risks on technology
	Firm's attitude toward adopting the technology
	Firm's confidence about adopting the technology
Corporate culture	Whether firm adopted the technology early or late compared to other firms
	Leadership at the firm
	Presence of a champion for the technology at the firm
	Consistency and quality of leadership in support of the technology at the firm
	Improvement of management at the firm
	Firm's organizational and technical capabilities
	Application of prior knowledge to the technology
	Information flow
	Labor relations
	Firm's contractual commitments to a particular technology
Firm structure and organization	Size of the firm
	Firm's existing capital and infrastructure and their compatibility with the technology
	Firm's ownership structure (investor-owned, municipally-owned, or cooperatively-owned)
	Amount of R&D conducted at the firm
	Firm's investment in improving capital and processes
	Firm's existing physical capacity for clean technologies
Characteristics of sector	Alliances among firms within the sector
	Knowledge sharing among firms within the sector
	Knowledge sharing between the sector and other sectors
	Whether country adopted the technology early or late compared to other countries
	Size of the existing energy system before the technology
	Fragmentation or monopoly within the sector
Domestic politics, preferences, and policy	Public support and preferences
	Shareholder support and preferences
	Political support and preferences
	Relationship with government
	Government R&D
	Government-sponsored conferences and technical support
	National pride
	National security benefits from the technology
	Presence or absence of a domestic policy encouraging the technology
Regulation	Presence or absence of a policy regulating the technology
	Uncertainty about future regulation/incentives
	Resistance to technology change from sources outside the firm
International politics, preferences, and policy	Perceptions of international community and international markets
	Risk of sanctions
	Presence or absence of an international policy encouraging the technology
Technological characteristics	Gains in efficiency or quality, cost reductions, or environmental benefits from technology
	Number of competing types/designs of the technologies to choose from
	Availability of information on the technology
	Time and cost to learn how to use new technology
	Intellectual property barriers to using the technology
	Compatibility of technology with existing systems
	Environmental problems or benefits related to the technology
Miscellaneous external conditions	Special conditions that enabled adoption of the technology

Table 1. Nine possible factors driving technological change. Factors were derived from the literature and presented to interviewees for prioritization after open-ended questions. Factors are not meant to be orthogonal or mutually exclusive but rather were established to cover different potential participant perspectives on the transformative drivers in the technology/country context

The Proalcool program supported the ethanol industry through quotas and price floors and ceilings. Consumers were guaranteed not to pay more than 65% of gasoline price at the pump, which created an incentive for production. At the same time, there were tax incentives for the production of pure ethanol cars, or E100, engines. In addition, all fuel stations in Brazil were required to have at least one ethanol pump, so consumers knew they could refuel. Further, only ethanol pumps were open on weekends. Also, banks were only allowed to provide financing to consumers for E100 vehicles, and taxes were higher on gasoline-fueled cars. In addition, freight subsidies were given to the transportation of ethanol and there was a mandatory ethanol blend with gasoline, which started at 5% and increased to a current 20-25% blend level.

In addition, Brazil dominated sugarcane technology and products, which meant that it did not have to rely on external knowledge. Support went also to research in developing high-yield cane varieties and improving ethanol fueled engines. The sugarcane mills were very open to new developments and shared knowledge and technologies. Mill consultants also played an active role in transmitting technology to mills and improved mill production processes. Finally, equipment manufacturers Dedini and Zenini also played a crucial role in ethanol production.

Economic Deregulation and Ethanol Decline

Three factors reduced the ethanol market: reduced oil prices, increased sugar prices, and reduced government support. During the 1980s, the price of oil fell, and ethanol became less competitive with gas. In addition, the new constitution of 1988 started to liberalize and reduce government involvement in the economy, funds for the Proalcool program ceased in 1989, and IAA was dissolved. Further, sugar mills began to export sugar, realizing higher sugar prices in the international market. Consumers began to have difficulty in obtaining ethanol, so demand for E100 cars decreased and automobile manufacturers produced fewer of them. By 2000, E100 cars were only available by special request. Many mills went bankrupt, and inefficient mills were closed or consolidated. In addition, the national oil company, Petrobras, had succeeded in finding oil off the coast, so the energy question was not seen as so pressing to the government.

The Flex Fuel Engine: The Second Ethanol Expansion & the Current Ethanol Market

The second ethanol movement was initiated almost entirely by the private sector via the development of flex fuel engines, which brought stable ethanol demand to the market and supported a solid integration of ethanol into the fuel market. In addition, the government set the price for ethanol, and research had dramatically improved production so that the ethanol price was competitive with gasoline. Currently, ethanol prices are very competitive at gas stations, and consumption of ethanol is higher than pure gasoline. The firm structure has become more and more important; with mergers and acquisitions, there are almost 30 billion dollars in movement.

b. Bioenergy in Sweden: Narrative Responses

Municipal Responses to the OPEC Oil Crisis

The 1973 OPEC oil crisis prompted serious concerns in Sweden about the long-term economic consequences of sustained high energy prices and the security implications of sustained high levels of oil import dependence. Swedish leaders ultimately considered a transition to bioenergy a necessary and expedient solution to the country's extensive use of oil for electricity and heat production, since a large number of Sweden's municipalities already had both municipally owned electric utilities and district heating (DH) systems in place. Since most Swedish municipalities were also situated close to forests and related industries that produced abundant streams of biomass wastes (e.g., logging operations, sawmills, and paper manufacturers), the switch from imported oil to domestic biomass as a boiler fuel was a relatively easy one.

The first DH systems in Sweden dated to the 1940s and were originally built both to provide heat for industrial processes and to alleviate the often severe air quality problems stemming from coal use and coking, that had plagued urban centers for decades. During World War II, the ease of fuel switching that DH systems facilitated was also considered a great advantage in the midst of the uncertainty and insecurity of wartime. With the onset of the OPEC oil crisis and rising concerns about acid rain, the combination of established DH networks with domestic forest biomass fuels presented municipal governments across Sweden with a ready pathway to clean, secure, and affordable energy.

The decentralized nature of Sweden's political system also played an important role in the country's transition to bioenergy. Sweden's 288 municipalities are relatively independent administrative and political units that collect a significant share of their respective budget revenues through taxes levied locally and exercise a high degree of administrative and political autonomy. As such, municipalities were the main drivers behind Sweden's transition to the use of bioenergy, and the strategic alliances that municipalities formed with forest industry associations, sawmills, and the transportation industry played important roles in facilitating the knowledge exchange and easy adoption of biofuel technologies. Municipal governments embraced biomass energy early on, recognizing that its adoption would keep a larger share of revenues within their respective administrative boundaries, creating jobs and spurring economic growth. Since all major domestic constituencies (i.e., the forest, transportation, paper, and lumber industries, municipal and national governments, power producers and the general public) saw the transition to biofuels as advantageous, no significant political obstacles impeded its progress.

Policy Drivers of Sustainable Bioenergy in Sweden

As fossil energy prices fell in the late 1980s and 1990s, so did economic incentives for investment in alternative energy sources. By then, however, climate change concerns had emerged as a key driver behind the switch to biomass energy. To sustain both interest in and incentives for investment in bioenergy and other renewable energy sources, Sweden's national government adopted two policies that have provided a stable regulatory environment for renewable energy: a tax on the carbon content of fossil fuels to equalize the relative costs and benefits of investing in fossil and renewable energy technologies and a Green Certificate (GC) program that required fossil power plants to purchase offsetting credits from non-fossil energy producers.

The Green Certificate program complemented the push effect of the carbon tax by creating a pull toward renewable energy generation and DH systems, since owners of wind, bioenergy, and other renewable electric plants received direct payments from electricity consumers. The program also provided government grants to assist companies and municipal governments to invest in new renewable energy facilities. Following the institution of these two policies in the early 1990s, bioenergy's share of final energy use in Sweden more than doubled to approximately 30 percent by 2009. Renewable energy now accounts for more than 60 percent of Sweden's primary energy supply.

c. United States Nuclear Power: Narrative Responses

Post-World-War-II "Atoms for Peace"

The demonstrated power of nuclear energy to kill wartime enemies gave way to a push for nuclear energy to make electricity, as articulated by President Eisenhower's "Atoms for Peace" programs. There was a promise of electricity "too cheap to meter," coupled with rising demand, which gave nuclear a luster – one respondent called this "magic" associated with the new technology. Participants agreed there was a very visible champion in Navy Admiral Hyman G. Rickover, who essentially chose the light water reactor. Electricity demand was rising at 6% or more per year, with the expectation that this rate would go on indefinitely, and costs were expected to decline as companies gained experience with building nuclear plants. Despite the uncertainties abound, from technical to financial, the federal government gave the strongest possible support; massive government subsidies were very effective in the early years. The Atomic Energy Commission (AEC) (1946-1974) regulated nuclear energy, working with the congressional Joint Committee on Atomic Energy to devise processes for siting, waste management, and research and development – all essential to the industry's development.

The Rapid Expansion of Nuclear Power

Until the late 1960s, nuclear power became an increasingly important part of meeting the overall energy demand growth. The Price-Anderson Act (1957) and other regulations minimized the financial risks of building nuclear plants, firms were eager to build, and costs declined as bigger generators were built. In addition, concerns about the environmental impact of coal burning led to a reluctance to build coal-fired plants until uncertainties about regulation were settled. In contrast, the US government was in the business of funding new technologies, from development through deployment. Many plants were built while regulations were evolving, and the AEC operated fairly independently. Utilities had a felt mission to serve rising demand, and construction firms took pride in being part of the nuclear expansion.

Curtailment

In the 1970s, anti-nuclear forces, always present as a deep distrust of the military foundations of nuclear as well as environmental concerns, increased their activities at the same time that economic downturns, rising energy costs, and lower demand made nuclear power less attractive. The 1979 Three Mile Island accident was a visible "break point" for nuclear, but the conditions of change were already present before this accident.

d. Sweden Nuclear Power: Narrative Responses

Military Beginnings

The Swedish nuclear program – as one interview respondent put it – all started in 1945 when a US delegation made an unannounced visit to Sweden to look at the uranium deposits, which, while of poor quality, were some of the largest in Europe. Sweden did not end up doing business with the United States, but after World War II, the Swedish government realized that nuclear weapons were the weapons of the future, and the country desired an effective deterrent weapon as it sat neutral between NATO and Russia. It was quickly realized that Sweden had the capacity to develop such nuclear weapons through heavy water reactor projects that could produce weapons grade material.

The government founded Atomenergi, a state-owned nuclear research company, to run a research center in Studsvik and develop nuclear reactor and weapons technology. And in the late 1950s, Atomenergi and Vattenfall, the state-owned utility, designed and built the first heavy water reactor demonstration plant in Agesta, which started up in 1963. Surprisingly, the technology was developed independently, as opposed to getting a license from a country like the United States that had already developed its nuclear program. Agesta successfully produced electricity and could put out small amounts of weapons material, but it was considered too small. A plant in Marviken followed, but the ambitious design made it too unstable for start up. It was never completed but turned into an oil-fired generation plant. But by that time, in late 1960s, support and need for a nuclear weapons program had dwindled and officially ended when Sweden signed the Nuclear Non-Proliferation Treaty at the end of the decade.

The Nuclear Build-out

After WWII, hydropower propelled Sweden into an industrial revolution, quickly surpassing the rest of Europe in GDP per capita by 1970. The country saw a three percent economic growth per year and an increased quality of life, but the government realized that they were running out of rivers. Coal- and oil-fired power plants became an option, but the environmental impacts were quickly seen as unacceptable. Energy independence also became more important, especially with the oil crises occurring during that time. Nuclear power became the obvious choice, especially since the large base loads already fit into the pre-existing electricity provision and distribution systems under the large-scale centralized production of hydropower. The government, specifically under Prime Minister Tage Erlander, spent much money in research and development on heavy water reactors through Atomenergi in Studsvik.

At that time, however, private companies started to complain about the government's monopolistic reign on nuclear power. Asea, an electrical engineering company led by Curt Nicolin, took the risk to develop its own light water reactor technology, again without a license. Asea had previously worked many hydropower projects and was also a subcontractor on the Marviken plant. And in 1965, Asea signed a contract Vattenfall to build Oskarshamn Unit One, which came on the grid in 1972. In the mid-1970s, the government-owned Atomenergi forced a merger with Asea, becoming Asea Atom, a 100 percent civil company. Together with Vattenfall, and a large cadre of newly-trained nuclear engineers coming out of just a few universities, 12 nuclear power plants were built and operated in Sweden over the next decade.

The Growth of Anti-Nuclear Sentiment

By the end of the 1970s, the political tone had changed in Sweden, challenging the safety and impact of nuclear technology. The four-decade reign of the Social Democratic party ended when the Centre Party gained control in Parliament. Its leader, Gunnar Hedlund and his advisor, physicist and Nobel Laureate Hannes Alfvén, thought nuclear power to be extremely dangerous. The advent of the environmental movement, Rachel Carson's book, and the Three Mile Island nuclear accident in 1979 culminated in a moratorium on construction and a public referendum on nuclear in 1980, resulting in a request to phase out nuclear by 2010.

As the century came to a close, pressure was placed on the government by citizens and other countries to close two reactors in Barsebäck, which eventually happened in 1997. The deal, however, came with an informal agreement that the 2010 phase out was no longer required. This meant that the government could continue, and has to this day, upgrading the reactor units in the existing plants, extending their life to 55 or even 60 years. For the foreseeable future, nuclear power will remain a large part of the Swedish power grid. Issues of safety and waste, especially, remain. Companies like SKB, were created to deal with waste in a manner that will ensure future safety for Sweden, its citizen, and the environment.

Discussion

The responses for part two of the interviews are outlined in **Table 2**. This portion of the interview protocol asked participants to select, from a group of nine options, the factor(s) they considered most important in influencing the direction of technological change in their sector. **Figure 1** depicts the same data but instead as a fraction of total responses in that country-sector combination, allows for easier intercomparison among cases of different Ns. As evident from **Figure 1**, a high fraction of participants, in all cases, emphasized domestic policy as a strong determinant in the diffusion (or lack of diffusion) of the two major energy technologies. For this category, at least 70% of all participants in every case ranked it as a top factor. All participants in Nuclear-US (N=6) and Bioenergy-Brazil (N=12) named this as a top factor; over 80% of Nuclear-Sweden participants (N=7) also named it. Technological characteristics were identified as an important factor by greater than 80% of participants in 2 of 4 cases (again, Nuclear-US and Bioenergy-Brazil). Sector characteristics, Corporate culture, and Regulation were identified by more than 40% of participants in 2, 3, and 2 cases, respectively. Interestingly, Regulation was named relatively frequently (>80%, N=6) for Nuclear-US, but the other sectors did not mention this factor as frequently.

	Bioenergy		Nuclear	
	Brazil	Sweden	USA	Sweden
N	12	11	6	7
Factor				
Domestic Policy	12	8	6	6
Technological Characteristics	10	4	5	2
Sector Characteristics	3	5	2	3
Corporate Culture	0	5	3	3
Regulation	1	5	5	0
Miscellaneous	3	2	1	2
Decisionmaking in Firm	1	1	2	1
Firm Structure	0	4	0	1
International Policy	3	0	1	0

Table 2. Participants' assessments of the "most important" or "determinative" factors behind the technological transformations in the nuclear/bioenergy

systems in their own countries. Caution must be applied in drawing statistical conclusions because (1) samples were not random and (2) participants were allowed to include up to three factors in the "most important category". However, the weight of evidence indicates that domestic policy, technological characteristics, and sector characteristics were dominant factors in most contexts.

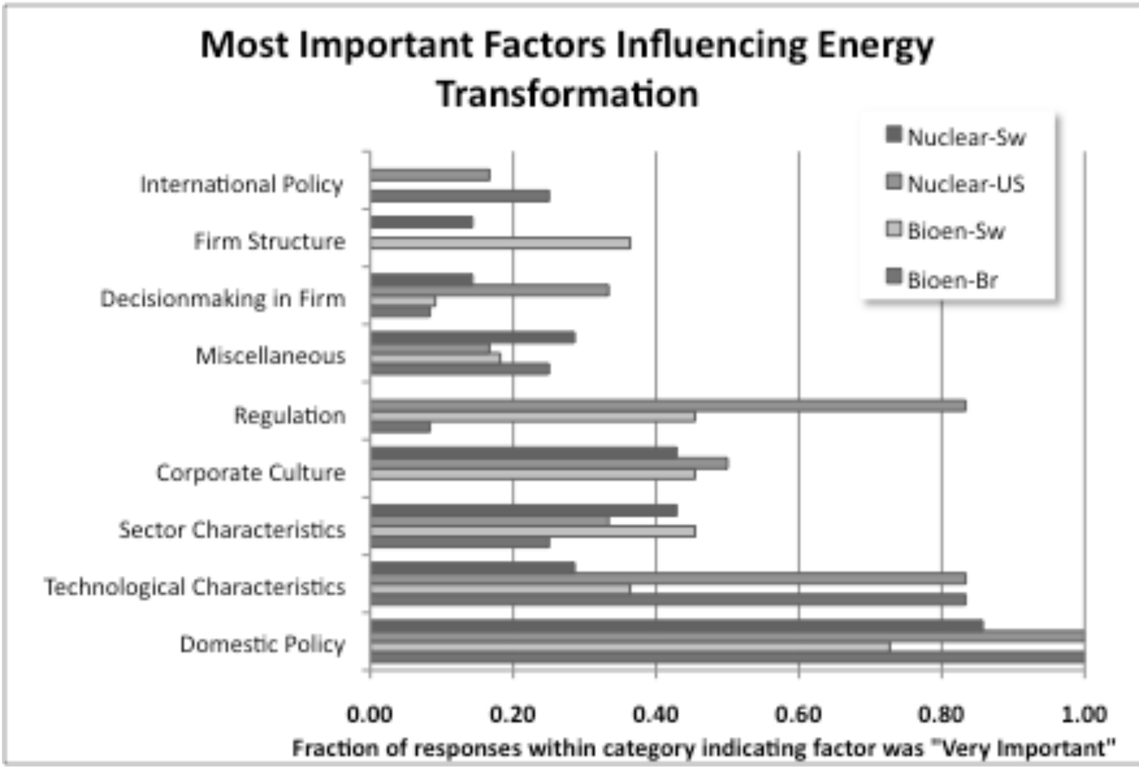

Figure 1. Fraction of responses by participants indicating that each factor is "very important" or "determinative", grouped by factor. Total number of interviewees is 36, and N for individual cases is given in **Table 2**

Individual cases had noteworthy variations as well. **Figure 2** clusters the responses across to the four individual cases. Bioenergy-Brazil presents perhaps the most dramatic illustration of the importance of non-economic factors, with fully 12/12 participants ranking domestic policy and 10/12 identifying technological characteristics of ethanol as a very important factor. Bioenergy-Sweden also showed emphasis on those two factors, but their importance was not as exaggerated with respect to other factors (Sector characteristics, Corporate culture, and Regulation). The Nuclear-US case participants emphasized Domestic policy, Technological characteristics, and Regulation. Domestic Policy was a more pronounced point of agreement in the Nuclear-Sweden case, with other factors lacking strong consensus. The Bioenergy-Sweden case also saw a substantially greater response for Domestic Policy. Perhaps most noteworthy, however, was that the largest fraction of participants across all cases identified Domestic Policy as a very important factor in determining the trajectory of their technology.

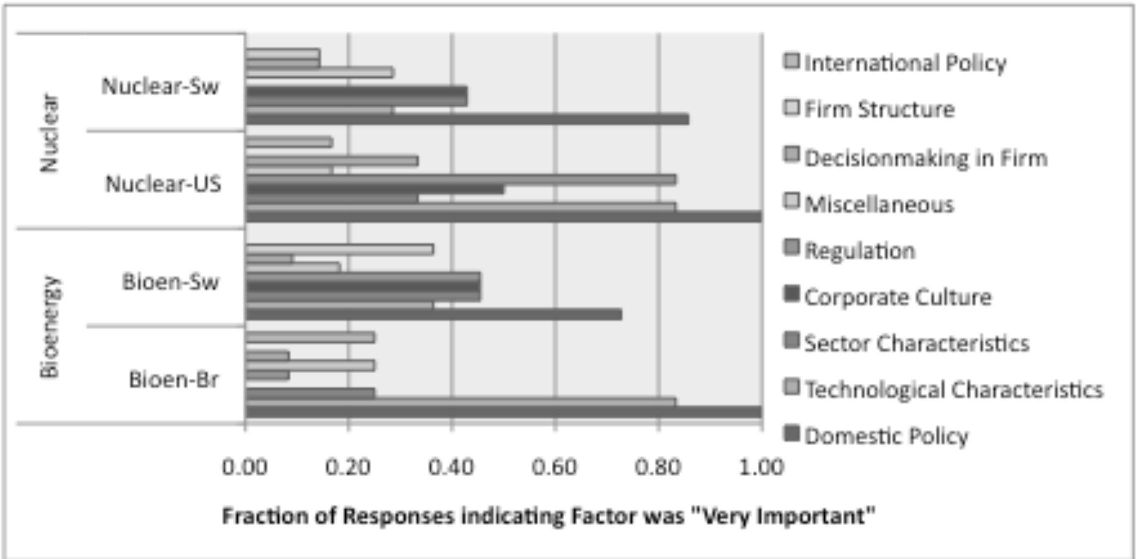

Figure 2. Fraction of responses by participants indicating that each factor is "very important" or "determinative", grouped by case (country/sector). Total number of interviewees is 36, and N for individual cases is given in **Table 2**.

Conclusion

In summary, this paper presents results from four cases in which low-carbon energy technologies experienced a substantial growth in the past 50 years: Bioenergy in Sweden and Brazil, and Nuclear Power in Sweden and the United States. Through interviews with key participants and experts, we traced not only the history of each technology in each country but also asked participants to select the factors they deemed most important in that technological trajectory. Across both technologies and all three countries, "domestic politics, preferences, and policy" was identified as a very important factor by the largest fraction of participants. With some variation across cases, "Technological characteristics" was also identified as a very important factor. A smaller fraction of participants in all cases identified "sector characteristics" and "regulation" as very important factors. Factors that were not mentioned frequently include "international policy," "firm structure," and "firm decisionmaking characteristics."

These results, combined with the narrative histories assembled for each country-sector case, illustrate the large degree to which major energy technology transformations are dependent on non-economic factors. While we can certainly acknowledge that pricing externalities properly may drive economies toward a lower-carbon economy, it is not at all clear that such policies are either forthcoming or feasible across a wide swath of the global economy. Indeed, for the cases we present here, externality pricing was a following, and not a leading factor, to technological changes. Instead, the changes occurred as part of domestic policy that was targeting goals such as domestic economic competitiveness, energy security, and respect for existing industries. As such, understanding these factors better, and how best to influence them, may be a more productive path to emissions reduction than focusing on pricing mechanisms.

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Appendix: Description of Factors

Factor	Description	Question	Quality	References
Decisionmaking characteristics of firm	Firm's willingness to take risks on technology	Is your firm generally more risk-averse or risk-taking about technology decisions?	Willingness to take technological risks	Heymann 1988, Rogers 1995, Kemp & Volpi 2008, Rotemberg & Salomer 2000, Shapira 1994, Nelson and Winter 1982, Dosi 1988, Tidd et al. 1997, Petts et al. 1998, Andrews 1998, Kline & Rosenberg 1986, Utterback 1994, van Someren 1995, Chattery 1995
	Firm's attitude toward adopting the technology	Why did your firm adopt or not when it did?	Attitudes toward adopting the technology	Montalvo 2006 & 2008
	Firm's confidence about adopting the technology	How easy did your firm think it would be to implement the new technology?	Self-efficacy in adopting technology ("perceived behavioral control")	Ajzen 1991, Montalvo 2006
Corporate culture	Whether firm adopted the technology early or late compared to other firms	How many firms in your country had already adopted nuclear/ethanol technology?	Whether firm was an early or late adopter	Nelson 1981, Stoneman & Diederen 1994, Grübler 1997, Malone 2003 [book]
	Leadership at the firm	How important was individual leadership or management in the development or implementation of nuclear/ethanol technology at your firm?	Leadership factors	
	Presence of a champion for the technology at the firm	Was there a champion for nuclear/ethanol technology within your firm?	Presence of a champion/charismatic leadership	Rosenberg 1982 [book], Malone & Runci [no digital]
	Consistency and quality of leadership in support of the technology at the firm	Was there strong and consistent leadership on nuclear/ethanol technology within your firm?	Degree, stability and wisdom of administrative sponsorship	Nonaka & Peltokorpi 2006 [book], Montalvo 2008, Carr [no digital]
	Improvement of management at the firm	Did management at your firm improve as nuclear/ethanol technology was implemented?	Managerial improvement	Malone 2004 [no digital]
	Firm's organizational and technical capabilities	How much expertise, training/capacity, and experience did your firm already have in the area of implementing nuclear/ethanol technology?	Organizational and technical capabilities of the firm	Moreira & Goldemberg 1999, Montalvo 2008, Lin et al. 2009, Penrose 1959, Collins 1994, Collins et al. 1988, Leonard-Barton 1992, Rosenbloom and Christensen 1994, Teece and Pisano 1994, Teece et al. 1990, Panda and Ramanathan 1996, Grant 1996
	Application of prior knowledge to the technology	Did your firm's knowledge about another technology aid in the implementation of this technology?	Knowledge spillovers	Argote & Epple 1990, Malone 2003 [book], Nonaka & Peltokorpi 2006 [book]
	Information flow	How would you characterize information dissemination and cross-departmental communication?		

	Labor relations	How important were workforce concerns or labor relations in the development or implementation of nuclear/ethanol technology?	Labor-related factors	Hughes 1983 [book]
	Firm's contractual commitments to a particular technology	Was your firm already contractually committed to any particular technology?	Contractual commitments to a particular technology	Walker 2000
Firm structure and organization	Size of the firm	How large is your firm relative to other firms in your sector?	Firm size	Constant 1987 [book], Rose & Joskow 1990
	Firm's existing capital and infrastructure and their compatibility with the technology	How compatible was existing infrastructure with the new nuclear/ethanol technology?	Existing capital and infrastructure: turnover and compatibility	Stoneman & Diederen 1994, Grübler 1997, Walker 2000, Malone 2003 [book], Malone 2004 [no digital], Kemp & Volpi 2008
	Firm's ownership structure (investor-owned, municipally-owned, or cooperatively-owned)	What is the ownership structure of your firm: investor-owned, municipally-owned, or cooperatively-owned?	Ownership structure	Constant 1987 [book], Rose & Joskow 1990
	Amount of R&D conducted at the firm	How much technology R&D does your firm engage in?	R&D	Stoneman & Diederen 1994
	Firm's investment in improving capital and processes	How much improvement/investment in capital goods and processes does your firm make?	Technological progress in capital goods and processes	*Dutton & Thomas 1984*
	Firm's existing physical capacity for clean technologies	Did your firm already have an environmental management systems or had it made any other similar investments?	Absorptive capacity (physical) for clean technologies	Kemp & Volpi 2008
Characteristics of sector	Alliances among firms within the sector	Are the firms in your sector very networked, i.e. are there alliances and cooperation?	Presence of strategic alliances and networks	Nelson 1981, Lin et al. 2009
	Knowledge sharing among firms within the sector	How much do firms within your sector share information?	Knowledge spillover among firms	
	Knowledge sharing between the sector and other sectors	How much does your sector share information with other sectors?	Knowledge spillover among sectors	Rosenberg 1994 [book]
	Whether country adopted the technology early or late compared to other countries	Did your country adopt nuclear/ethanol technology late or early relative to other countries?	Whether market is an early or late adopter	Grübler 1997, Malone 2003 [book]
	Size of the existing energy system before the technology	How large was the existing energy system before implementation of nuclear/ethanol technology?	Extent of energy system	Grübler 1997
	Fragmentation or monopoly within the sector	Is your industry characterized by either fragmentation or monopoly?	Industry structure	Brown et al. 2007
Domestic politics, preferences, and policy	Public support and preferences	Was there public support for nuclear/ethanol technology?	Public support/preferences/risk perception	Pickett 2002, Malone 2003 [book], Jacobsson & Lauber 2006, Runci, Clarke, & Dooley 2006, Montalvo 2006 & 2008, Howard et al. 2009 [no digital], Malone & Runci [no digital]

	Shareholder support and preferences	Was there shareholder support for nuclear/ethanol technology?	Shareholder support/preferences/risk perception	Montalvo 2006 & 2008
	Political support and preferences	Was there support from political leaders for nuclear/ethanol technology?	Political support/commitments to a particular technology	Walker 2000, Jacobsson & Lauber 2006, Howard et al. 2009, Nemet 2009, Malone & Runci [no digital]
	Relationship with government	Does your firm have a positive relationship with government and regulators?	Relationship with government	Pickett 2002
	Government R&D	Is there much government-sponsored R&D of nuclear/ethanol technology?	Government R&D	Astrand & Neij 2006, Foster, Hildén, & Adler 2006, Jacobsson & Lauber 2006, Runci, Clarke, & Dooley 2006, Lin et al. 2009, Nemet 2009
	Government-sponsored conferences and technical support	Does the government sponsor conferences on nuclear/ethanol technology or provide other forms of technical support?	Government-sponsored knowledge transfer	Taylor, Rubin, & Hounshell 2003
	National pride	To what extent was the choice of ethanol/nuclear technology related to perceptions of national prestige, strength, and cohesion?	Nationalism	Kovarik 2007
	National security benefits from the technology	Is nuclear/ethanol technology perceived as linked to increased national security?	National security	Pickett 2002, Astrand & Neij 2006, Kovarik 2007
	Presence or absence of a domestic policy encouraging the technology	Was there a domestic policy in place encouraging adoption of nuclear/ethanol technology?	Presence or absence of domestic policy	Lesbirel 1990 [no digital], Stoneman & Diederen 1994, Moreira & Goldemberg 1999, Astrand & Neij 2006, Jacobsson & Lauber 2006, Montalvo 2008, Kemp & Volpi 2008, Malone & Runci [no digital]
Regulation	Presence or absence of a policy regulating the technology	Were there standards or a policy in place regulating nuclear/ethanol technology?	Regulatory pressure	Rosenberg 1969, Taylor, Rubin, & Hounshell 2003, Foster, Hildén, & Adler 2006 [book], Montalvo 2006, Kemp & Volpi 2008
	Uncertainty about future regulation/incentives	Were future environmental policies and regulation of nuclear/ethanol technology uncertain?	Regulatory/incentive uncertainty	Brown et al. 2007, Nemet 2009
	Resistance to technology change from sources outside the firm	How much resistance to technology change was there from different actors, institutions, and the economic and political systems?	Degree of conservative momentum in socio-technical systems	Hughes 1983 [book], Grübler 1997, Astrand & Neij 2006, Kemp & Volpi 2008
International politics, preferences, and policy	Perceptions of international community and international markets	Was there international support for nuclear/ethanol technology, politically and/or economically?	Perceptions of international community (politics and markets)	Pickett 2002
	Risk of sanctions	Was there a risk of sanctions from the international community for implementing nuclear/ethanol technology?	Risk of sanctions	

	Presence or absence of an international policy encouraging the technology	Was there an international policy in place encouraging adoption of nuclear/ethanol technology?	Presence or absence of international policy	
Technological characteristics	Gains in efficiency or quality, cost reductions, or environmental benefits from technology	Were there many technological opportunities associated with nuclear/ethanol technology, e.g. efficiency, quality, cost reductions, or increased environmental performance?	Technological opportunities	Klevorick et al. 1995, Montalvo 2008, *[Maybe (from Nemet 2009): Rosenberg 1974, Nelson and Winter 1977]*
	Number of competing types/designs of the technologies to choose from	Were there competing types of nuclear/ethanol technology to choose from?	Number of competing technologies/diversity of designs	Grübler 1997, Malone 2003 [book], Nemet 2009
	Availability of information on the technology	Was information on nuclear/ethanol technology readily available?	Availability of information on technology	Nelson 1981, Soete & Turner 1984, Stoneman & Diederen 1994, Kemp & Volpi 2008
	Time and cost to learn how to use new technology	Was learning to use nuclear/ethanol technology very time and cost intensive?	Time and cost to learn how to use new technology	Soete & Turner 1984
	Intellectual property barriers to using the technology	Were there any intellectual property barriers to acquiring the new nuclear/ethanol technology?	Intellectual property landscape	Soete & Turner 1984, Brown et al. 2007
	Compatibility of technology with existing systems	What complementary technologies, capabilities, and/or existing infrastructure were available to help the diffusion process?	Complementary technologies	Rosenberg 1982 [book], Grübler 1997, Malone 2003 [book], Kemp & Volpi 2008
	Environmental problems or benefits related to the technology	Does nuclear/energy technology have many environmental problems or benefits?	Environmental quality/issues	Moreira & Goldemberg 1999, Pickett 2002
Miscellaneous external conditions	Special conditions that enabled adoption of the technology	Were there any specific initial conditions that you feel enabled the spread of nuclear/ethanol technology?	Specific initial conditions	Rosenberg 1982 [book], Grübler 1997