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Coalitional Cohesion in Technology Policy

The Case of the Early Solar Cell Industry in the United States

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Abstract

The paper traces the rise and decline of solar cell commercialization efforts during the 1970s and early 1980s in the United States. It shows how technology policies for photovoltaic appliances gained and lost support in a time of increasing uncertainty about future resource supplies and the future of energy provision. Contrary to conventional explanations of the long history of failures to commercialize renewable energy technologies that emphasize path dependencies around established energy technologies, this paper explains the rise and decline of early solar cell policies from the perspective of internal sectoral developments. It demonstrates that cohesion among political economic supporters was critical for public perceptions of the intermediary success of the effort, to continuous investment by industry, and to the maintenance of political support. The paper suggests that support for new industries and technologies is dependent on sectoral order among supporting groups over time. The case of the early photovoltaics policies illustrates how the failure to keep groups unified and committed undermined the implementation of the technology policies, weakened the credibility of the developmental effort, and ultimately led to a decline in political support. The paper contributes to recent debates about the conditions of successful industrial and technology policies by demonstrating that network failures have an important political dimension if ruptures of sectoral cooperation feed back on state support for the respective industry or technology.

Keywords: technology policy, renewable energy, institutional change, governance, innovation

Zusammenfassung

Der Aufsatz zeichnet den Aufstieg und Niedergang früher Kommerzialisierungsinitiativen für Solarzellen in den USA während der 1970er- und 1980er-Jahre nach. Er erklärt, warum Förderprogramme für Photovoltaikanlagen in einer Zeit wachsender Unsicherheit über die zukünftige Gestalt von Energieversorgungssystemen Unterstützung erhielten und wieder verloren. Im Unterschied zu konventionellen Erklärungen der Geschichte von Fehlschlägen in der Kommerzialisierung von Solartechnologien, die größtenteils die Beharrungskräften etablierter Energieerzeugungssysteme herausstellen, fokussiert der Aufsatz interne sektorale Entwicklungen. Er zeigt, dass Kohäsion unter Unterstützern kritisch für die Wahrnehmung der Effektivität der Unterstützungsprogramme, für kontinuierliche Industrieinvestitionen und für die Stabilität staatlicher Förderung war. Der Fall der frühen Photovoltaikprogramme zeigt, dass nachlassender Zusammenhalt unter beteiligten Akteuren die Implementation der Unterstützungsprogramme und die Glaubwürdigkeit des Entwicklungsanlaufs untergraben hat und letztlich zum Abflauen staatlicher Förderung führte. Der Aufsatz trägt zu neueren Debatten über die Bedingungen erfolgreicher Industrie- und Technologiepolitik bei, indem er zeigt, dass industrielle „Netzwerkfehler“ eine politische Dimension haben, sobald Unterbrechungen sektoraler Kooperation auf die staatliche Unterstützungsbereitschaft zurückwirken.

Schlagwörter: Technologiepolitik, erneuerbare Energien, institutioneller Wandel, Governance, Innovation

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1 Introduction

Over the past decade, there has been a revival of scholarly interest in technology and industrial policies (Berger 2013; Block 2008; Block and Keller 2011; Mazzucato 2013; Schrank and Whitford 2009; Piore 2008; Rodrik 2004). While the last major debate on the forms and functions of industrial and technology policies was fueled by the industrial turmoil of the 1970s and 1980s and the related discussion about the structures of European and Japanese political economies (Graham 1992), the current wave of interest goes back to a convolution of developments. Important triggers have been sluggish economic growth since the financial crisis of 2008, the rapid expansion of Chinese manufacturing exports, the widespread expectation that digital services are just beginning to transform the global economy, and the realization that all measures to contain global warming necessitate accelerated industrial and technological restructuring on an unprecedented scale.

Recent sociological contributions differ from earlier debates about the state's role in industrial development in developed countries by being less concerned with questions of state–business relations, work organization, organizational structures, or market dynamics, and more with problems of interfirm organization – with *network failures* (Schrank and Whitford 2011; Whitford 2005). There are historical reasons for this shift of focus. Technological change, the globalization of supply chains, and changes in business organization and central growth drivers seem to have lessened the importance of firm-based and technological "targeting" and for the bureaucratic "steering" of industrial development (Block 2008; Rodrick 2004; Sabel and Zeitlin 2004). Instead, the facilitation of learning across organizational boundaries and the promotion of ecosystems that support continuous business and product innovations take center stage in recent debates about industrial and technology policies. This pushes the state into a role Fred Block (2008, 190–4) circumscribed with the functions of *opening windows*, *brokering*, and *facilitation* and Lester and Piore (2004, 56–73), writing about the shifting role of management, compared to that of a "hostess at a cocktail party."

I aim to add to this line of research about the network dimension of industrial and technology policies with an argument about the *political effects* of the organization of interfirm dynamics, or what I call the challenges of coalitional cohesion in bringing about

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The paper builds on a monograph which gives a comprehensive account of the development of the photovoltaic industry; see Ergen (2015). I would like to thank Jens Beckert, Richard Bronk, Helen Callaghan, Betsy Carter, Gerhard Fuchs, Lukas Haffert, Sebastian Kohl, Filippo Reale, and Alfred Reckendrees for their comments on earlier versions of the paper. All remaining shortcomings are mine.

industrial and technological change. Long-term efforts to bring new technologies to market or develop a footing for new industries, the argument goes, can be undermined if developmental coalitions of firms, societal groups, and state agencies fracture over time and thereby unravel political support.

This conceptual argument goes against one of the main theoretical approaches in historical work on alternative energy technologies: that of virtuous cycles between state support, industry growth, and technological development. One of the main puzzles of historical research on alternative energy technologies, and in particular on solar cells, is their odd pathway of century-long failures to gain a foothold in energy supply systems followed by rapid development since the 1990s. For 150 years, solar technologies were regularly seen as the basis of virtually free and inexhaustible resource supplies to power industrial societies in the future (Abelshauser 2014; Butti and Perlin 1980, ch. 5–14; Heymann 1998; Mener 2001). Nevertheless, initiatives to commercialize solar technologies continuously failed. The direct usage of solar energy has a 150-year history of more or less workable prototypes, big promises, and failed realization. For brief periods of time, firms set up to market solar technologies made inroads into new markets and advanced designs and production. Still, commercialization for non-niche applications in modern energy supply systems has proven elusive for over a century. Equally stagnant paths of industrial development – also stretching from the *fin de siècle* technological euphoria into present day *risk society* – mark the histories of modern wind turbines and electric cars.

As we know now, the commercial success of the main renewable energy technologies in use today was contingent not on genuine technological breakthroughs or game-changing innovation, but on continuous incremental development (which notwithstanding added up to game-changing improvements in the technology over time). Hence, the history of failures to bring alternative energy technologies to market has been explained with the rigidities of the energy sector which prevented new technologies from establishing a basis for long-term development. Modern energy provision systems are of such scale, complexity, and political economic interlocking that they assume what Thomas Hughes called *technological momentum* – “mass, velocity, and direction …, an inertia of directed motion” (Hughes 1983, 15). Extreme varieties of path dependence worked as entry barriers to new and comparatively exotic technologies. Without an immediate opportunity to enter energy provision systems, the production of new technologies was not extended and their development was not accelerated. Without investments, in turn, entry into energy markets was out of the question. Entry barriers were not just economic in nature. Institutional, political, and cultural structures aligned with established energy technologies permeate modern societies. These range from patterns of economic and social life adapted to continuously running power plants to political structures securing resource supplies and vice versa. Socio-technical rigidities prevented solar technologies from securing the resources necessary for what economic historians have called *experiential learning* – continuous learning between research and development, production, distribution, and usage (Abelshauser 2014; Garud and Karnøe 2003; Mener 2001, ch. 1.3).

Given the obvious barriers to their commercialization, historical studies have increasingly focused on niche-systems to explain how alternative energy technologies survived more than a century of industrial stagnation (e.g., Bruns et al. 2009; Jacobsson, Sandén, and Bångens 2006). Idealistic supporters created a "sheltered space" for the respective technologies, allowing for continuous development despite lacking opportunities in markets. Once sufficiently advanced and in the presence of windows of opportunity such as the recent politicization of human-induced climate change, the industry was able to break out, mobilize state support, capture new markets, attract further supporters, and get into virtuous circles of industrial development (see Jacobsson and Lauber 2006). Put differently, after passing a threshold of technological maturity and initial political backing, the respective technologies could profit from the same forces of cumulative advantage that had held them back for decades.

My paper suggests qualifications to the story of structural barriers to the commercialization of solar technologies and, by extension, to simple depictions of the political economy of industrial and technological change. Explanations of the problems of renewables commercialization that emphasize the structural rigidities of modern energy systems certainly capture important aspects of the history of solar technologies. Structural rigidities defined *the challenges* the technologies faced. The fact that solar technologies played no significant role in energy provision limited their potential to mobilize supporters, attract resources, and develop, which in turn solidified their marginal position. However, niche-theories are less helpful for understanding what went wrong in attempts to *overcome* barriers to commercialization.

In the following, I present an analysis of the most ambitious early attempt to commercialize solar cells, roughly lasting from 1972 to 1986 in the United States, which hints at the crucial role of cohesion among supporters and at the counter-intuitive effects of intermediary successes on the structure of support coalitions. Contrary to niche-accounts of technological change, which treat both the alignment of supporters' interests and the positive effects of successes on coalitional stability as givens, the case of the early solar cell industry demonstrates that the cohesion of political economic coalitions can be highly fragile over time. From the 1970s, support for solar technologies depended on comparatively heterogeneous coalitions, industrial ecosystems, and networks. Continuous industrial development and political backing was contingent on cooperation and alignment within the respective industries, research communities, and social movements. As shown in the following, the attempts to commercialize solar cells in the 1970s and 1980s failed because they did not manage to keep different groups unified and integrated.

The paper is divided as follows. Section 2 lays out some fundamental conceptual ideas on the problems of continuity and coalitional alignment in industrial development. Section 3 presents the case of early American photovoltaic support in the 1970s and 1980s. It gives context to technology policies for photovoltaics by briefly describing societal reactions to the energy crisis of the 1970s, shows how supporters established a commercialization initiative for the technology, and describes the failure of the plans and the near-complete fragmentation of the support coalition. Section 4 discusses the processes illustrated and suggests how the paper's main argument connects to research results from other empirical domains.

2 Coalitional cohesion and the politics of technological change

The reallocation of resources across political economic systems is rarely a smooth and easy process. Common problems of reallocation processes range from convincing sufficient numbers of social groups of future opportunities for employment, profit, prosperity, and other benefits to dismantling resistance by established interests. Larger processes of technological change, such as any transformative change in the economy, are precarious socio-political processes (cf., Beckert 2016, ch. 6 and 7; Stinchcombe 1997, 12–15). Specific problems of processes of technological and industrial change re-emphasize the characteristic at the core of my argument that positive feedback loops between support policies and supporting coalitions are contingent outcomes of political processes. I discuss four organizational problems of technological policies before pointing to their systematic consequences for the study of policy feedback in industrial and technology policies.

First, the development of technologies – especially of those that are not "path-breaking" at the invention and prototype stages – requires outlays from multiple social groups over time, most importantly in terms of investment, the spread of information, institution-building, and state support. More demanding technological processes of technological development often have the quality that Schickler and Pierson, regarding institutions, referred to as *common carrier*-like (Pierson 2004, 109–10; Schickler 2001, 14–15). Such development processes mean different things to different groups and actors and they rely on that kind of "multifaceted" support. To further understand the role of *continuous* inputs over time it is important to correct a common and misleading intuition about the interplay between new technologies, production, and usage. In his history of economic theory, Blaug highlighted a tendency in economic thought to conceptualize technological innovations as predominantly "external priors" to production. In practice, he observed that the "vital difference for an individual firm is not between known and unknown but between tried and untried methods of production." He continues:

> The convention of putting all available technical knowledge in one box called "production functions" and all advances in knowledge in another box called "innovations" has no simple counterpart in the real world, where most innovations are "embodied" in new capital goods, so that firms move down production functions and shift them at one and the same time. (Blaug [1962] 1990, 704)

Blaug's observation can be pushed further: in many industrial and technological fields, firms *can only* shift production functions *if* they move down on them, extend production, recoup resources, and learn by manufacturing (for extensions of the argument, see Garud and Karnøe 2003; Rosenberg 1982, ch. 5–7). Similar processes are at play at the junctions of production, distribution, consumption, and usage (e.g., Schwartz Cowan 1987) and in the constitution of industry-specific expertise for the effective design and implementation of technology policies between state agencies, industries, the sciences, and stakeholders (e.g., Ziegler 1997). Compared to "one-shot" problems of social mobilization, the safeguarding of continuous inputs over long time periods is a strenuous task. Both external shocks (good examples are cyclical price movements for fossil fuels) and endogenous developments can endanger continuous commitments by relevant groups. Such problems are at the core of arguments which claim that successful industrial policies result from working attempts to build developmental coalitions rather than from mere transfers and subsidies or product creations. "The key to facilitating the growth of a new sector," Evans observed in his comparative studies of IT industry policies, "was … creating the conditions that led entrepreneurial groups to identify their interests with the growth of the sector and commit resources to it" (Evans 1995, 210).

Such commitments are regularly dependent upon one another, representing the second of the four organizational problems of technological policies. Complex technologies consist of numerous components which are functionally interrelated. The same holds true for socio-economic regimes around modern technologies. Technological development is subject to problems resembling those described by early development economists arguing that poor societies require a "big push" across sectors to enter industrialization (e.g., Rosenstein-Rodan 1943). On the one hand, interruptions in individual investment activities or instances of institutional work may have ramifications across development processes. On the other, developmental activities are faced with a series of coordination and collective action requirements to maintain complementary inputs and collective learning. As worked out by Gawer in her study of Intel's efforts to maintain and guide innovation by third party manufacturers of components for personal computers, dominant firms attempt to foster continuous complementary innovation through standard setting, developmental guidance, and platform activities (Gawer 2000). In a series of case studies on early stage innovation processes, Lester and Piore documented how new designs and technologies emerged from continuous exchange (or "conversations") between technical specializations and industrial fields (Lester and Piore 2004). Studies of institutional reforms by Weir show that support coalitions often suffer from what might be called *alignment problems*. As all subgroups of internally heterogeneous support coalitions have a multitude of avenues to further their interests, institutions depending on shared support may lose their backing over time if support coalitions incrementally fragment (Weir 2006; Weir, Rongerude, and Ansell 2011).

The third organizational problem concerns the fundamental uncertainties that plague processes of technological change, gravely worsening the above problems. Optimal technological designs and production techniques, the feasibility of cost projections, the receptivity and behavior of buyers, and possible societal effects of technological change are to a large degree only accessible *after the fact*. Beckert suggests that this gives prime importance to the formation of expectations, unifying images of the future and shared stories in the economy (Beckert 2016). As outlined in sociological research on the role of expectations in the emergence of new technological fields, shared expectations have constitutive, organizing, and, to a certain degree, "self-fulfilling" effects (Borup et al. 2006; van Lente 1993). Continuous development across industries and supporting groups requires not just the initial emergence of such shared expectations, but that these expectations be patched up in times of revisionary experiences, defended against rival stories about the future, and maintained in the face of disillusionments, failures, and developmental crises.

Fourth, processes of industrial and technological change are fraught with latent and manifest distributional conflicts. Competing technical solutions, the division of labor in new industrial fields, and rival plans by different social groups all feed into processes of socio-economic change. As described by studies of industrial crises and adjustment, getting from common interests to coordinated action in processes of socio-economic change is an arduous task (see, for example, Borrus 1983; Esser, Fach, and Väth 1983, on the politics of change in the steel industry). Whitford's studies of manufacturing organization in the United States document such problems in the maintenance of developmental communities across organizational boundaries. Such communities (or networks) are vulnerable to misunderstandings, factional conflicts, and problems of collective action based on distributional questions – despite obvious joint gains (see, e.g., Schrank and Whitford 2011).

Where does this leave us with respect to industrial and technology policies? In their critique of rigid accounts of path dependency and policy feedback, historical institutionalists in political science have been pointing for a long time to *dynamic problems* of institutional stability and reproduction. Over time, they argue, the stability of institutional regimes depends on continuous renegotiation, updating, patching up, and political work (Streeck 2003; Streeck and Thelen 2005; Thelen and Kume 2006). This argument, on the one hand, shifts the analytical focus from questions of initial distributions of resources between social groups, initial coalition formation, and momentous legislative action towards questions of implementation, institutional effects over time, and incremental change (Hacker and Pierson 2014). On the other hand, it has led to various follow up questions with respect to the failure of policies to bring about intended enduring effects and to sustainably reorganize interest groups, coalitions and social systems (Jacobs and Weaver 2014; Patashnik and Zelizer 2010). A processual variety of incremental decline particularly relevant for the case of the early photovoltaic industry has recently been explored by Mark Mizruchi in his history of the American corporate elite since the 1970s (Mizruchi 2013). Mizruchi questions an old intuition with respect to social cohesion. While the idea that social unity leads to power and the ability to reach common goals is well documented and theorized, the reverse relationship has rarely been investigated systematically. Initial successes of collective action, Mizruchi claims, can feed back on groups' unity in deeply troubling ways. By removing the initial reasons for cohesion, groups may lose conventions, habits, institutions, and the sense of moderation necessary to work together in heterogeneous coalitions and to overcome potential conflicts.

The emphasis on the "post-enactment politics" of policies in recent institutional analysis can be transferred to the stabilization of new industries and the support of new technologies. As laid out above, processes of technological change thought of as decade-long complex enterprises are riddled with social sources of potential failure and disintegration. In recent sociological scholarship a similar argument has led researchers to conceive of the emergence and stabilization of socio-economic structures as social movement-like processes (Fligstein 2001). Similar to social movements, the emergence of socio-economic structures for these scholars rests on the ability of actors to forge coalitions, motivate others to cooperate, unify expectations and problem perceptions, and attract supporters. Put differently, new socio-economic structures emerge on the basis of a minimum of social order and maintained coalitional alignment.

It is exactly this problem of overcoming the state of fissure endemic in unsettled social formations that photovoltaic policies in the 1970s failed to come to terms with. The case of the photovoltaic industry in the 1970s and 1980s discussed here demonstrates that the commercialization of new technologies involves the above problems of coalition building and social mobilization and shows how actors can fail to control them over time.

3 The rise and decline of early photovoltaic commercialization initiatives

Basic varieties of current solar cell technologies were comprehensively developed in the 1950s. With few exceptions, they ended up in a complex of research institutions, small technology-oriented firms, and Western satellite programs. It was not until the early 1970s that future energy supply systems became sufficiently politicized for that complex to attempt to push the technology towards economic maturity. In 1973, a loose coalition of activists, firms, state agency representatives, and researchers developed plans for an unparalleled coordinated attempt to scale up production, develop markets, and incrementally lower the cost of the technology.[1] As soon as the envisioned commercialization programs were initiated, however, interests among supporters started to diverge, the support coalition incrementally fell apart, and the endeavor as a whole became

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[1] In the following I refer to this collection of actors as the photovoltaic "sector." An alternative way to refer to them as a collective would be the concept of a social field. The concept of social fields – as it was used by, among others, Pierre Bourdieu and Neil Fligstein – has major advantages to that of sectors in that it emphasizes power struggles and structures of domination. As my argument does not primarily rely on these explanatory factors I stick to the notion of sectors which is more prominent in everyday language and comes with less theoretical baggage.

increasingly fragmented. Despite unprecedented financial and political support, firms resisted investing and refused to expand the production of widely understood technologies. Activists, Congress, firms, government, and research institutes, in turn, developed diverging agendas and goals. Eventually, the initial commercialization plans were not implemented and the programs devolved into a renewed fractured high-risk research effort. When the conservative reaction and the oil glut of the 1980s eventually put an end to broad principled support for photovoltaic commercialization, an essentially gridlocked sector fell back into insignificance, while the initial developmental narrative came to be seen as an early misstep based on flawed thinking.

The energy crisis and the rise of energy technology policies

Well before the politicization of climate change from the mid-1980s, societies had forcefully tried to push renewable energy technologies towards economic maturity. The center of these efforts was in the United States. Between 1973 and the early 1980s, the American political economy was home to an unparalleled attempt at state-building in the energy sector (Ikenberry 1988). A centerpiece of this enterprise consisted of a series of policies to commercialize alternative energy technologies ranging from controlled photosynthesis and nuclear fusion to coal liquefaction. To understand the emergence and form of these policies, it is instructive to think of the early 1970s' American energy sector as being at the juncture of two developments: the incremental politicization of energy supplies from the early 1970s, and the environmental and "left-libertarian" movements that took hold in the 1960s and challenged the social order of the postwar decades. Together these two developments led societies away from reactive and more standard policy repertoires in energy sector governance and into concerted attempts to secure future room for maneuver via the commercialization of new technologies.

Technology policies in the energy sector were by no means new to the 1970s. Political efforts to generate a civilian atomic energy industry had grown from the mid-1950s onwards and were accelerated during the 1960s. The governance, design, and extension of the coal, gas, and oil industries have basically been organized by states and international diplomacy. In 1952, a widely-discussed report by the so-called *Paley Commission* called for state-building in peace times regarding the supply of resources to the American economy, an idea still being echoed in 1962 with regard to energy.[2] Still, public energy R&D before the 1970s did not have anywhere near the central status we take for granted

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[2] See The President's Materials Policy Commission. 1952. *Resources for Freedom: A Report to the President.* Five vols. Washington, DC. On energy, see volumes 3 and 4. Notably the experts asserted that "it is time for aggressive research in the whole field of solar energy – an effort in which the United States could make an immense contribution to the welfare of the free world" (vol. 4, 220). On the 1962 initiatives, see Committee on Natural Resources. 1962. "Natural Resources: A Summary Report." Washington, DC: National Academy of Sciences and National Research Council, 13–15.

today. In a 1966 report that summarized a review originally requested by the Kennedy administration, for example, experts relieved the administration by stating that since "no true emergency nor compelling opportunity is foreseen, the total energy R&D expenditures look reasonable. Of course, if heavier reliance were to be placed on imported resources, the level of R&D expenditures should undoubtedly *decrease*."[3]

This situation changed at the beginning of 1970s. Already before the oil shock of late 1973, Richard Nixon warned publicly about a looming energy crisis and requested comprehensive reports about the future of American energy supplies and on possible measures to secure them.[4] After the first OPEC price increase and the beginning of the embargo of October 1973, he escalated the rhetoric and kicked off the now four decade-long American quest for what he called energy independence:

> Today the challenge is to regain the strength that we had earlier in this century, the strength of self-sufficiency. Our ability to meet our own energy needs is directly limited to our continued ability to act decisively and independently at home and abroad in the service of peace, not only for America but for all nations in the world. … Let us set as our national goal, in the spirit of Apollo, with the determination of the Manhattan Project, that by the end of this decade we will have developed the potential to meet our own energy needs without depending on any foreign energy sources.[5]

From the beginning, significant parts of Nixon's administration questioned the feasibility of his Project Independence 1980 (De Marchi 1981, 448). One of the first documents spelling out pathways towards energy independence, the above-cited report by the AEC published in December 1973, already talked about 1985 as an intermediary stage towards self-sufficiency, a horizon later re-affirmed by the Ford administration. In addition, the administration was riddled with programmatic conflicts in how far government interference with oil supplies (especially import restrictions and price controls) was not actually at the heart of the crisis (De Marchi 1981, 466–7; Jacobs 2008; Jacobs 2016; Laird 2004, 103–8). Despite these conflicts, the administration over the following years built unprecedented governmental capacities for planning and the restructuring of the American energy system (Ikenberry 1988). Perhaps most important, the turmoil of the energy crisis together with the feeling of a broader socio-economic watershed changed the rhetoric and outlooks on energy. As if it were the most natural thing in the world, top bureaucrat Frank Zarb looked back at the beginnings of Project Independence and cherished that,

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[3] Energy Study Group. 1966. "Energy R&D and National Progress. Findings and Conclusions: An Interdepartmental Study." Washington, DC, 14, as cited in Lambright and Teich (1979, 142), emphasis by Lambright and Teich.

[4] U.S. Atomic Energy Commission. 1973. "The Nation's Energy Future: A Report to Richard M. Nixon." Washington, DC..

[5] Richard M. Nixon. 1973. "Address to the Nation About Policies to Deal with the Energy Shortages." Washington, DC.

> Two years ago, this nation faced the prospect of importing twelve million barrels of foreign oil every day by 1985. Today, as a result of those parts of the program that are now law, that prospect has been reduced by four to five million barrels daily. That's barrels of oil we won't import: that's American dollars that will stay in our own economy; that is, in short, progress.[6]

Important for understanding the trajectory of this state-building effort is the fact that most decisive steps towards Nixon's 1980 goals failed during the following years – oil and gas decontrol, the speed up of nuclear energy development, the quick revival of American coal, and numerous conservation measures. Most initiatives with expected distributional effects were eventually defeated or watered down in increasingly chaotic political battles (Kitschelt 1983, 177–79). Under Nixon's, Ford's, and Carter's administrations there emerged an increasing emphasis on technology policies to escape these political stalemates with regard to restructuring the energy sector in the future. In 1974, public research and development for the energy sector was centralized in the *Energy Research and Development Administration* (ERDA), a direct descendant of the non-regulatory parts of the gigantic Atomic Energy Commission. Initially ERDA was staffed with 7200 direct employees and an annual budget of 3.6 billion dollars and seen by many as an institutional replication of the Manhattan Project in the energy sector.[7] In 1977, ERDA, merged with several regulatory bodies, formed the basis of the newly established Department of Energy.

While the government sought near- and medium-term relief in a revival of American coal, untapped oil reserves on US territory, a hastening of nuclear energy development, and conservation, coalitions between segments of an increasingly activist Congress and various organizations and groups managed to force a series of renewable energy activities into the reorganization initiatives (see Figure 1 for a budgetary overview). Via separate bills, Congress institutionalized a range of reporting, support, and research obligations in the new regime for energy technology policy. Importantly, the establishment of a research laboratory with an exclusive focus on renewable energies (called the Solar Energy Research Institute, SERI, and later the National Renewable Energy Laboratory, NREL) was mandated by Congress, which from then on took center stage in US renewables development. These support measures were repeatedly extended over the next decade, notably from 1977, and eventually there existed a broad regime for renewables commercialization. Most of these initiatives targeted the 1990s – or, more often, "the year 2000" – as the time for momentous effects of new technologies on energy provision. They nonetheless changed medium-term outlooks. Renewables were advertised as alternatives to next-generation nuclear reactors, for example, and were presented as benign avenues towards future energy independence.

The social bases of these initiatives were the environmental and radical social movements of the late 1960s and 1970s. Even before the energy crisis, both movements were

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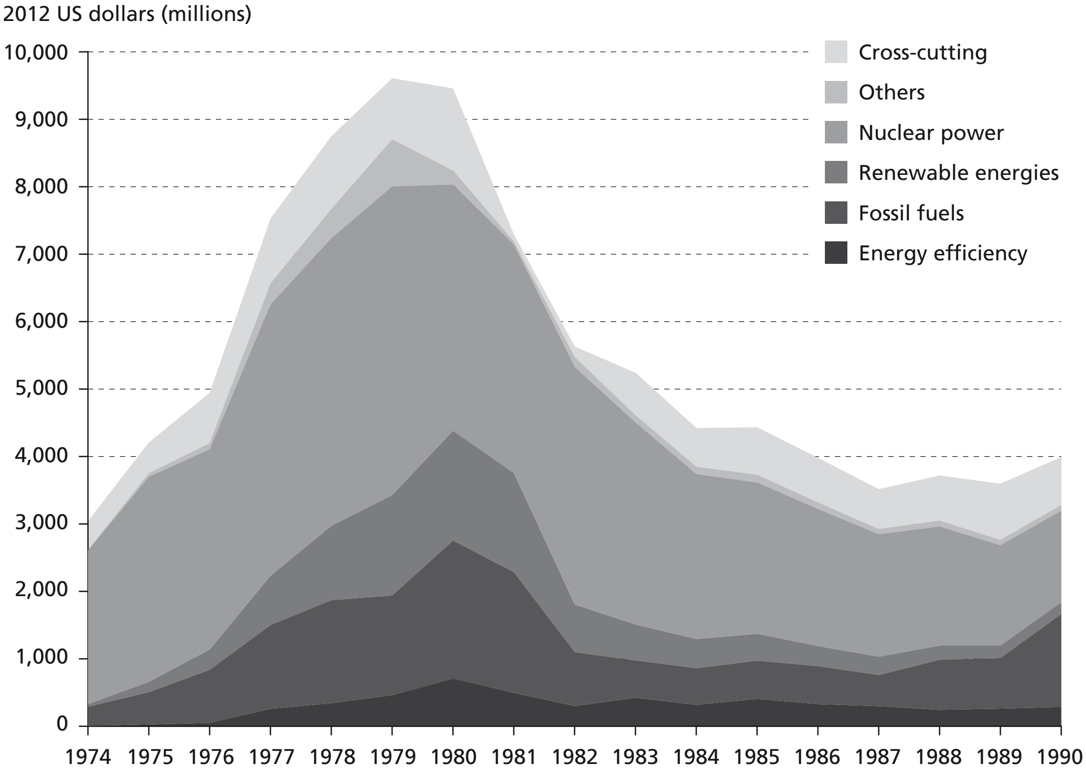
[6] Frank G. Zarb. 1976. "Remarks Prepared for Delivery before the Illinois Solar Energy Conference." Chicago Circle Auditorium, University of Illinois. Chicago.

[7] On the contemporary hopes surrounding ERDA, see Alexander (1976).

Figure 1 Annual spending for energy research and development in the US, 1974–1990

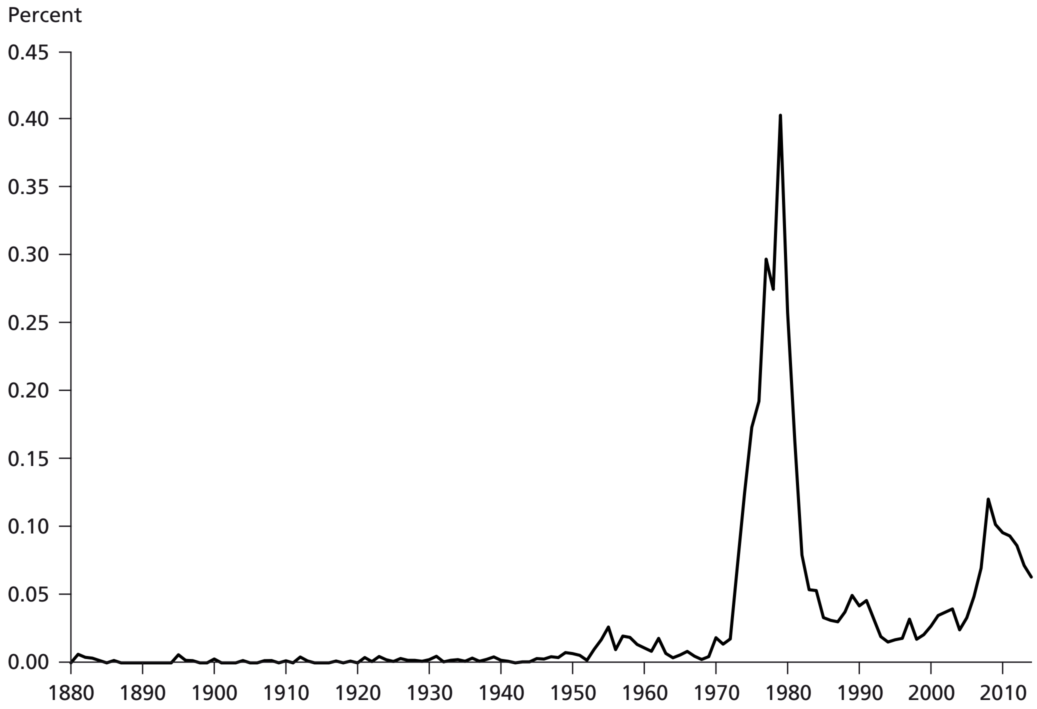


Source: International Energy Agency.

loosely acquainted with energy issues via anti-pollution, anti-nuclear energy, and anti-nuclear armament protests. At the height of the energy crisis, several motives of the new social movements reemerged in political conflicts about the future of energy provision, while energy became a subject of intense political activism. In the debates following the publication of, among other publications, *The Limits to Growth* (Meadows 1972), earlier thinking on environmental overreach merged with peak oil concerns and the critique of the postwar economic growth model. The following decade of popular criticism of the oil and utility industries and of established energy policies took up numerous earlier motives from anti-nuclear protests, as well as associated attitudes against economic concentration and elite political bargaining. Amory Lovins, scientist at the environmentalist social movement organization Friends of the Earth and one of the intellectual protagonists of early energy activism, discussed the watershed of the 1970s' energy policies as a watershed of societal development. "In an electrical world," he argued,

> your lifeline comes not from an understandable neighborhood technology run by people you know who are at your own social level, but rather from an alien, remote, and perhaps humiliatingly uncontrollable technology run by a faraway, bureaucratized, technical elite who have probably never heard of you. Decisions about who shall have how much energy at what price also become centralized – a politically dangerous trend because it divides those who use energy from those who supply and regulate it. (Lovins 1976, 92)

Figure 2 Share of articles mentioning solar energy, 1880–2013



Source. New York Times Chronicle.

On one hand, the support for renewable energies as well as the opposition to nuclear energy, the accelerated exploitation of fossil fuel reserves, and continuities in the structure of the energy provision industry incrementally became highly politicized matters. On the other, movement activists were slowly drawn into more technocratic activities. Jimmy Carter, for example, made Denis Hayes, co-organizer of the first Earth Day and prominent figure in the environmental movement, director of the Solar Energy Research Institute (SERI), and he publicly supported various movement events to raise public awareness of the benefits of renewables, such as the so-called Sun Day. When Barry Commoner, another important figure of the early environmental movement, praised "The Solar Transition" in 1979 he did so mostly by lecturing his readers about the "true costs" of various energy technologies, about the economics of oil, and about the effects of various energy systems on economic growth, inflation, the trade balance, and employment (Commoner 1979).

The movement towards renewables support had remarkable repercussions in the media and in public discussions (see Figure 2 for an illustration). Rarely did political speeches about the future of the American energy system miss out on at least mentioning the potential of "solar energy." This anchoring in the public imagination and in various institutions formed the backdrop of initiatives to commercialize photovoltaics during the 1970s.

The growth of photovoltaic support

Crystalline silicon photovoltaic cells, the most important photovoltaic technology which structurally has remained unchanged until today, were first developed in a focused way in 1954 at AT&T's Bell Labs. While the 1954 findings immediately gave rise to public hopes for a near-term solar revolution, Bell Labs researchers quickly realized that production costs of the technology precluded commercial application in the supply of energy. Photovoltaic technologies were taken up in the American satellite and space programs in the late 1950s. The extension of the photovoltaic development in the satellite programs saved the technology from full commercial insignificance. By the early 1970s, the technology was almost exclusively developed in a loose network of public research institutes, space program-dependent small firms, and corporate laboratories. The two decades in the space programs were a blessing and a curse for the development of the technology. On the one hand, photovoltaic cells had a clear and stable competitive advantage when it came to reliably powering satellites over long periods of time in space. A small but constant stream of resources and talent were available to the technology. This was the basis on which photovoltaic development could continue to profit from advances in solid-state physics, semiconductor research and manufacturing, and silicon processing as it had at Bell Labs. Space applications, on the other hand, led to very specific developmental foci and manufacturing techniques. They emphasized longevity improvements under environmental conditions in space, efficiency enhancements, weight reduction, and excessive failure-proof manual manufacturing, none of which helped directly with lowering the costs of cells or easing their application in energy provision on earth (see Mener 2001, 268–73; Perlin 1999, 51).

Mener has presented historical evidence that the networks around solar use in space began renewed discussions about the feasibility of terrestrial photovoltaic usage already in the mid-1960s (Mener 2001, 306). Pioneering entrepreneurs from at least 1969 explored the possibilities to lower the costs of solar cell production for use on earth. Chemist Eliot Berman, for example, convinced the oil corporation Exxon to finance one of the first new silicon photovoltaic departments (Perlin 1999, 52–53). From 1973, Berman's Solar Power Corporation routinely marketed photovoltaic modules for about a fifth of the price common a few years earlier – for around 20 dollars per watt peak nameplate capacity instead of 100 dollars (126.95 and 634.76 CPI-deflated for 2013; ibid., 54–55). In the early 1970s a number of oil concerns started, coopted, or took over small photovoltaic firms. As Mener puts it, in the late 1970s it became "almost common courtesy" for oil concerns to own a photovoltaic producer (Mener 2001, 305). Besides moderately renewed interest among businesses, public institutions also started to fathom the potential of terrestrial photovoltaic usage at the beginning of the decade. Both NASA and the National Science Foundation (NSF) began to work on contours of a research and development program for photovoltaics at the beginning of the decade (Kitschelt 1983, 286; Mener 2001, 316–17, 320–21).

In 1972 the two agencies assembled a first comprehensive panel of experts from science and business to lay out the potential of a public hastening of renewables development. The resulting report contained nearly all later motives for public commercialization support. The "possibilities for the economic use of solar power," the experts asserted,

> given reasonable R&D support, appear much better than generally realized … There are also international benefits in making a viable solar technology available to the world as well as balance of payments and national security benefits in limiting our almost inevitable dependence on foreign energy sources … The most environmentally benign solar energy systems might be those of small scale that would fit into space already occupied by buildings … One can indeed imagine designing 'optimum size' environmentally oriented communities which would meet most of its energy needs from direct solar energy and the solar derived fuels from the local waste treatment plant.[8]

In addition, the report contained a path-breaking narrative about the reasons for the enduring high costs of photovoltaics and a corresponding vision for the way forward. While the experts admitted that production costs would have to go down by a factor of 100 to come close to the price levels required for non-niche terrestrial energy applications, they reasoned that a "significant part of this is expected to be gained through the required million-fold expansion of production rates and attendant automation."[9] The panel developed the mild technocratic vision that there were no basic technical or institutional barriers to photovoltaic commercialization, but simple problems of scale, incremental learning, and mass production.

This vision was solidified at a larger conference at Cherry Hill, NJ, that eventually started the first serious commercialization efforts for photovoltaics. Funded by the NSF, the conference assembled state agency representatives, manufacturers, researchers, and utility representatives to discuss the possibilities of a concerted effort to commercialize solar cell application. Held only seven days after the announcement of the Arab oil embargo, the conference discussions in parts slid into aspirational euphoria. Various manufacturers claimed to be able to meet cost goals for crystalline photovoltaic modules that had been considered illusionary just a few years earlier. Solarex's Lindmayer claimed that he would be able to produce modules for 10 dollars per watt peak immediately, given sufficient demand; Heliotek's Ralph presented prospective milestones of 2.50 by 1978 and 30 cents by 1983.[10] When pressed by participants how he came up with module costs of 5 dollars at the research-intensive Radio Corporation of America, Paul Rappaport high-

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[8] NSF/NASA Solar Energy Panel. 1972. "An Assessment of Solar Energy as a National Energy Resource." Washington, DC, 8–11. Besides a lot of ideas about decentralized generation regimes, NASA for years advertised a gigantic photovoltaic platform in space, "beaming" the generated energy to earth. See Mener (2001, 306).

[9] NSF/NASA Solar Energy Panel. 1972. "An Assessment of Solar Energy as a National Energy Resource." Washington, DC, 52.

[10] "Photovoltaic Conversion of Solar Energy for Terrestrial Applications." Vol. 2: "Invited Papers." 1973. Workshop Proceedings, Cherry Hill, NJ, October 23–25. Organized by Jet Propulsion Laboratory, California Institute of Technology, 8, 9.

lighted the thought underlying this quasi-tournament. “I don’t care if it is $20 a watt at the present time,” he argued, “We feel that *prices now are artificial* because demand is too limited.”[11] The NASA’s William Cherry pointed to the role government support had to play in this situation and reminded participants of the most-cited example at the time of the virtues of “learning curve-focused” state support:

> Definitely the government has got to do some pump priming … The semiconductor industry got started the same way … if you would look at the cost of semiconductors, you could see that there wasn’t much of a reduction over the years during the fifties. But as soon the large amounts of government expenditures dropped off, the prices started coming down, the competition went up, and those who could make it for the price stayed in the field. The same thing is going to happen with us.[12]

While many of the hopes for a rapid way forward focused on scale and experience considerations, others were primarily built on ideas about “advanced automation” notorious in the 1960s and 1970s (e.g., Noble [1984] 2011, ch. 8–10). The mostly manual production techniques inherited from the space programs were to be replaced by what Cherry Hill participants called a “sand in, cells out” approach.[13] Based on several new concepts for the production of cells – especially a saw-free technique for producing silicon wafers called edge-defined film growth (EFG) at Tyco, screen printing at STI, and polycrystalline silicon processing at Solarex – supporters hoped that sufficient demand would kick-start investment in dedicated advanced production facilities.[14] Amidst the various projections, the conference participants eventually agreed on the feasibility of a realistic pathway to commercialization. Until 1985, they reasoned, a concerted state-led initiative would allow the industry to build 50 MWp (megawatt peaks) of annual cell production capacity (up from 0.37 MWp in 1975) to lower the costs of the technology to 50 cents per watt peak (down from around 30 dollars in 1975).

Outside of the NSF/NASA environment, assessments of photovoltaics in the aftermath of the oil crisis were mixed at best. The early Project Independence plans in line with earlier recommendations by the AEC were rather skeptical of near-term commercialization of the “solar-electric approach” and focused their renewables recommendations on much simpler devices for solar heating and cooling. It took some years of institutional entrepreneurship for broader circles to take up the vision of cheap semiconductors in energy. Popular Science, for example, devoted its December 1974 title page to the new photovoltaic industry, summarizing that “dramatic technical developments can bring free energy into our big power.” While regularly citing problems of cost and storage,

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[11] “Photovoltaic Conversion of Solar Energy for Terrestrial Applications.” Vol. 1: “Working Group and Panel Reports.” 1973. Workshop Proceedings, Cherry Hill, NJ, October 23–25. Organized by Jet Propulsion Laboratory, California Institute of Technology, 11, emphasis added.

[12] Ibid., 57.

[13] Ibid., 19.

[14] “Assessment of the Technology Required to Develop Photovoltaic Power Systems for Large-Scale National Energy Applications.” 1974. Pasadena, CA: Jet Propulsion Laboratory, California Institute of Technology, 9, 12.

the New York Times in 1975 (August 8, 26) echoed solar energy supporters' claims that there were essentially two ways available to modern society to escape energy problems for good:

> Fuel to power nuclear fusion is nothing more exotic than ordinary sea water, but the technology of conversion requires massive reactor complexes. The second "ultimate" power source is the oldest source of energy known to man, the rays of the sun; the device for converting solar rays into electricity is small and harmless enough to fit into a baby's fist.

The first comprehensive planning report for renewables by ERDA already contained most of the reasoning and motivations reemphasized in Cherry Hill.[15] They became the basis of a series of ERDA-led commercialization programs – despite continued critique and contestation by non-solar planners at the R&D administration.

American technology policies for photovoltaics after 1974 were anything but monolithic. Funding for new basic technological varieties (especially for various compound semiconductors) was maintained. NASA for years supported conceptual work on its photovoltaic space station and there emerged a small but dedicated complex around new big power plant designs, so-called concentrators. Photovoltaic R&D was sponsored by numerous organizations ranging from corporate laboratories and the military to universities (Knight 2011). Still, the new spirit of optimism fueled the emergence of a more integrated ten-year commercialization program for standard crystalline silicon cells, which was led by Caltech's Jet Propulsion Laboratory (JPL) and was based on hopes for cost reductions through industrial upscaling. The so-called Low-Cost Silicon Solar Array (LSSA) Project attracted a remarkable array of firms and resources for the 1985 goals of Cherry Hill. From 1975, it systematically sponsored block buys of solar panels from the emerging manufacturing scene to disseminate knowledge, gather information, and utilize manufacturing capacity. The LSSA project contracted some of the most prolific firms in production technology, semiconductor processing, and various other fields to develop prototype equipment and work out feasibility studies. Between 1975 and 1977 LSSA suppliers had cut the cost of solar panels from around 30 to 15 dollars per watt peak. American panel production tripled in the same time to around 1.2 MWp.

These developments were successful in reinforcing the initial hopes and attracting supporters. Federal funding for photovoltaic research had been on the rise from 1970. By 1974, it had risen from about 1.7 to 34 million dollars per year. With the beginning of systematic support, it grew to around 86 million dollars in 1975 and 233 million in 1976. With the entry of the 95th Congress into the hastening process, the authorized funds for photovoltaic development climbed to around 400 million dollars annually between 1977 and 1980. Even so, in 1977 the National Photovoltaics Program was repeat-

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[15] "National Solar Energy Research, Development and Demonstration Program: Definition Report." ERDA-49. 1975. Washington, DC: Energy Research and Development Administration, Division of Solar Energy, III-14.

edly considered to be a remarkable success. "The Semiconductor Revolution Comes to Solar," *Science* headlined that year, stating enthusiastically that

> the federal photovoltaic research effort is credited by many observers as being perhaps the best conceived and most successful of the government solar programs … Not only is it achieving improvements in the efficiency and reductions in the costs of silicon solar cells at a more rapid rate than that projected by its plan, but it also appears to have stimulated private industry into activity. (Hammond 1977, 445)

Indeed, by the middle of the decade, numerous firms had worked on a multitude of technological projects and, at least in part, invested in new manufacturing capacity. The new terrestrial photovoltaic manufacturers made further inroads into several niche markets such as the lighting of buoys, uses in military special operations and the powering of repeater stations, remote communities, and anti-corrosion devices for oil pipelines. Much discussed was what was sometimes called the *Breeder Plant* by Solarex, a photovoltaic-powered factory for photovoltaic panel manufacturing (on the history of Solarex, see Berger 1997, ch. 11; Margolis 2002, 184–211). By far the largest success of the new developmental regime was its recognition by solar activist coalitions in Congress since 1977. As part of a surge in bills to support renewables (Lambright and Teich 1979), Congress – regardless of skeptical positions in the administration – in 1978 institutionalized the commercialization programs for photovoltaics in what it called the *Solar Photovoltaic Energy Research, Development, and Demonstration Act.* It claimed that "there appear to be no insoluble technical obstacles to the widespread commercial use of solar photovoltaic energy technologies," suggested 1.5 billion dollars for the support of public procurement and R&D support over a period of ten years, and reasoned that "the establishment of sizable markets for photovoltaic energy systems will justify private investment in plant and equipment necessary to realize the economies of scale and will result in significant reductions in the unit costs of these systems."[16] In addition, the young industry received support through numerous state-level initiatives, subsidized credit lines, tax credits, solar support components in foreign aid projects, export assistance, and new regulations for utilities to buy feed-ins from independent electricity producers (for a broad and still incomplete historical overview of government support for photovoltaic commercialization, see Maycock and Stirewalt 1981, 113–21).

Coalitional fragmentation and the decline of photovoltaic support

The development of the photovoltaic sector since the middle of the decade followed a surprising path. In multiple ways, the intermediate successes of the industry fed back onto the sector in disintegrating ways. While the sector had developed an unprecedented economic, technological, and political dynamic by 1977, support for the collective

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[16] "Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978." Pub. L. No. 95-590, 92 Stat. 2513 (1978), 95th U.S. Congress. Washington, DC.

scale-up of production declined, while political support coalitions increasingly fragmented. Even before the often-cited external shocks on the support of the technology – the rise of new conservatism to power in the early 1980s, the oil glut of the mid-1980s, and divestures by oil companies – the photovoltaic programs lost their grip on the development of the sector. The emerging problems of the commercialization initiatives grew out of three interrelated processes. First, projections for the development of the technology had self-undermining effects when it came to continuous and coordinated investment. Second, the rain of money on the industry led to a rediscovery of basic research, radical innovation, and proprietary development. Third, emerging distributional conflicts concerning the appropriate focus of the developmental effort weakened political unity.

None of the early planning documents left out graphical illustrations of the projections of Cherry Hill. These were either in the form of successive "stages" of development (from mono-crystal silicon growth to polycrystalline casting and finally to the direct growth of silicon wafers, for example) or in the form of continuous experience "curves" cross-plotting the growth of manufacturing capacity and cost improvements until 1986. Undoubtedly, these expectations helped to mobilize supporters for the developmental effort. Nonetheless, the *very same expectations* led to a hesitance on the side of the industry to invest in more capital-intensive manufacturing facilities. "The critical question is not whether a $2/Wp plant can be built," a baffled report diagnosed,

> but whether industry will be motivated to make investments in large-scale production facilities. These facilities represent major departures from, rather than gradual evolution of, the small-scale facilities currently used to manufacture arrays. They also represent a major increase in the fixed portion of total production cost and a commitment to a technology that is still advancing. Hence, the technological uncertainty is whether a $2/Wp plant will rapidly become obsolete as photovoltaic technology advances and thereby produce financial losses.[17]

Talk about the dangers of technological obsolescence was all over the sector prior to the bill of 1978. Asked for the funds necessary for entry into the industry, an FTC representative fully convinced by the developmental projections responded that, "if one assumes the initial investment will quickly become obsolete, so that an entirely new investment must be made within the planning horizon … $50 million should be adequate."[18] The problem of obsolescence was not just limited to experience curve reasoning. On the one hand, it had a competitive dimension to it. The warrant by the state to support the 1986 goals in effect meant that all firms making intermediary investments would have to witness focused public support for their future competitors. On the other, the further development of manufacturing technology was not independent of support poli-

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[17] Dennis Costello, David Posner, Dennis Schiffel, James Doane, and Charles Bishop. 1978. "Photovoltaic Venture Analysis: Final Report." Volume 1. SERI/TR-52-040. Golden, CO: SERI, 62.

[18] Jeffrey L. Smith. 1980. "Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems: Review and Critique." DOE/JPL-1012-45. Pasadena, CA: Jet Propulsion Laboratory, US Department of Energy, 76.

cies – manufacturers were expected to continuously come up with new and improved solutions. "In summary," JPL researchers affirmed after coming to terms with that logic,

> anticipated rapid technological change delays or prevents investments, biases facilities toward labor intensive processes and increases product prices. Thus, any attempt on the part of government to increase (say double) R&D expenditures will increase the tendencies [to delay or prevent investment].[19]

In discussing similar phenomena in historical case studies of other industries, parts of the JPL's photovoltaic group seemed to believe that they discovered a fundamental flaw in earlier thinking about the technology policies:

> It is inconsistent to plan a highly automated, capital intense production process in the midst of a rapidly changing technology. It is the program plan that is at fault and that should be changed – not the natural and socially correct reaction of private businessmen who will be reluctant to invest in such a situation.[20]

The reluctance to invest was not limited to the production of solar cells and modules. Similar reasoning existed in the production of solar-grade silicon products. Chemical concerns also talked about technological obsolescence to justify why they were not willing to contribute to the effort with dedicated production facilities. As JPL researchers summarized:

> Progress has been made in the Low Cost Solar Array Project … in developing new processes to produce low cost, semiconductor grade silicon. There is a high probability that the 1986 price goal ($14/kg compared to about $65/kg in $1980) will be achieved by one or more of these processes. Hence, the likelihood that a new process will be used in silicon production plants about 1986 leads to a reluctance to invest in Siemens-process new plants.[21]

Neither were silicon producers willing to make the first step in establishing a larger photovoltaic production chain. Working in the early semiconductor industry marked by extreme cyclicality, a Dow Corning representative, for example, told supporters that he would not be willing to risk overcapacities for the distant and uncertain hope of rising photovoltaic industry demand: "We got burned pretty well and there's not too much excitement to get burnt the second time."[22] Without extended and cheaper supplies of silicon, however, incentives for photovoltaic manufacturers to invest were dwindling as

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19 Jeffrey L. Smith. 1978. "The Industrialization of Photovoltaic Systems." Pasadena, CA: Jet Propulsion Laboratory, 19, emphasis added.

20 Jeffrey L. Smith, William R. Gates, and Tom Lee. 1978. "Historical Evidence of Importance to the Industrialization of Flat-Plate Silicon Photovoltaic Systems." LSA Task Report 5101-54, Vol. 2, DOE/JPL-1012-78/1. Pasadena, CA: Jet Propulsion Laboratory, 2-16.

21 "Silicon Materials Outlook Study for 1980–85 Calendar Years." 1979. JPL-79-110. Pasadena, CA: Jet Propulsion Laboratory, 7.

22 "Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978." Hearings before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration of the Committee on Science and Technology. U.S. House of Representatives, Ninety-Fifth Congress. First Session 1978, 111.

well. For a certain time, the hesitation of the industry to take care of intermediary investments led parts of the support close to the JPL programs to think about making the necessary first investments themselves. Some of the first drafts of the National Photovoltaic Program Plan still contained proposals for "experimental facilities" for production along the value chain to be operational by 1981–1985 and a government-owned "mass production plant" to be on line by 1985.[23] These proposals did not make it into the commercialization regime. In 1977, DOE representatives still called their exclusion "controversial," but pointed to the emphasis on demand-pull support favored by Congress and small businesses as well as to the lack of industry support for government-owned manufacturing facilities.[24]

In addition to the new investment trap, the American photovoltaic industry in the second half of the 1970s rediscovered basic research and hopes for radical innovation. The centrality of the LSSA initiative in the National Photovoltaics Program continuously declined in the second half of the decade. Over the years, there were numerous supporters breaking rank with the LSSA's concerted industrialization approach in public statements. Emerging demands ranged from a reorientation of the programs towards large concentrators and high-efficiency cell technologies to emphases on photovoltaics based on new semiconductor technologies (mostly so-called Thin Films). *After* the passage of the 1978 photovoltaic bill, SERI representatives, for example, claimed that

> it is crucial to develop an experimental research program in new semiconductor materials such as amorphous semiconductors or organic semiconductors. In fact, *it may be possible to take a fresh approach to photovoltaics.* Some scientists believe that a radical reduction in cost of solar cells could be achieved by an imaginative research program to uncover a very cheap thin-film material that has optical and electrical properties suited for solar cells.[25]

Congressional hearings for the 1978 support bill were crowded with entrepreneurs and researchers presenting new materials or approaches to the technology. "We are constantly harassed," a member of Congress complained in 1977, "by various enthusiasts with truly astounding claims of cost and performance improvements and schedules, all purporting to offer quick solutions to the energy crisis."[26]

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[23] Jeffrey L. Smith, William R. Gates, and Tom Lee. 1978. "Historical Evidence of Importance to the Industrialization of Flat-Plate Silicon Photovoltaic Systems." LSA Task Report 5101-54, Vol. 2., DOE/JPL-1012-78/1. Pasadena, CA: Jet Propulsion Laboratory, 2-16, 3-3.

[24] "Oversight on Photovoltaic Energy Conversion." Hearings before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration of the Committee on Science and Technology, U.S. House of Representatives, Ninety-Fifth Congress. First Session 1977, 9–10, 12.

[25] "Basic Research Needs and Priorities in Solar Energy." Volume 1. 1980. Golden, CO: Solar Energy Research Institute, 19–20, emphasis added.

[26] "Oversight on Photovoltaic Energy Conversion." Hearings before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration of the Committee on Science and Technology, U.S. House of Representatives, Ninety-Fifth Congress. First Session 1977, 2.

One of the most important and enduring technological deviations from crystalline cells were technologies based on amorphous silicon (a-Si). While far less efficient and stable than their crystalline alternatives, amorphous silicon panels were expected to be easier to manufacture and promised to circumvent some of the most arduous and costly steps in the production of standard solar panels (crystal formation, sawing, and processing). Importantly, after their development at RCA and transfer to ARCO Solar, a-Si technologies often formed the basis of one of the most important new niche markets for photovoltaics, the powering of small electronics devices like calculators and watches, which was to a large degree exploited by Japanese manufacturers. Large parts of the authorized funds for demand-pull support could not be absorbed by an industry refocusing on more basic and proprietary research (Hart 1983, 331). In the late 1980s around eighty percent of federal photovoltaic support went into basic research. In several ways, the renewed interest in breakthrough research grew out of the resource streams caused by earlier, more concerted developmental efforts that established expectations of a near-term photovoltaic revolution.

Diverging expectations with regard to technological foci were repeatedly at the heart of the political fragmentation of the sector and laid the groundwork for distributional conflicts. At the turn of the decade the industry consisted of roughly fifteen manufacturers that mostly focused on niche markets, and around 80 firms overwhelmingly working on laboratory-stage development (Roessner 1982, 121). In the consultations for the 1978 bill, research-intensive firms repeatedly criticized the demand-pull components of the programs. RCA, for example, suggested that "new technology or technologies are required. Therefore, the value to the Nation, as a whole, of a Government-sponsored yearly doubling of the existing market … is not clear."[27] Utilities, which supported the work on larger ground stations with high-efficiency materials, bemoaned a "'small is beautiful' bias" in the Congressional support initiatives.[28] Reporting from what it called the Southern California Solar Battle, the Chicago tribune quoted an opponent of development support for utilities, claiming that "[public] solar development offers the first serious possibility in this country of reversing the trend of monopoly control of the economy. The issue is ownership of the sun."[29] Niche market-focused manufacturers – often drawing on funds from their parent oil concerns – in turn spoke out against direct support for plant expansions. "It is a non-leveraging, costly application

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[27] "Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978." Hearings before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration of the Committee on Science and Technology, U.S. House of Representatives, Ninety-Fifth Congress. Second Session 1978, 117.

[28] Frank A. McCrackin. 1979. "Southern California Edison Company Comment on the JPL Draft 'Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems.'" In *Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems, Supplement: Review and Critique* (1980), edited by Jeffrey L. Smith, 41–42. JPL Publication 80-32. Pasadena, CA: Jet Propulsion Laboratory.

[29] Stephen Singular. 1977. "Solar Energy Battle Heats Up in California." *Chicago Tribune*, October 23, 241–44.

of Federal funds that virtually guarantees perpetual Government subsidy of obsolete technology," an ARCO Solar representative later testified. "If we were of the opinion that a new manufacturing plant would get us to $2.00 per Watt peak, *we* would build such a 25 Megawatt plant on our own."[30] Well-funded manufacturers instead demanded public assistance in the fields of international marketing, market access, and exports. In addition to the different viewpoints in the industry, agreement among supporting organizations declined over time. DOE officials repeatedly criticized the spending frenzy of the Solar Coalition in Congress. Regional SERI centers over time developed increasingly isolated plans and programs. Jimmy Carter himself, after signing the photovoltaics bill into law, publicly warned about the "risks involved in premature commercialization of solar photovoltaic technologies" and added that "It is still too early to concentrate on commercialization of photovoltaics."[31] Numerous hearings and reports since the mid-1970s criticized the photovoltaic programs for their stamping by big oil and elitist governmental agencies. In comparison to many simpler technologies, especially solar cooling and heating, the photovoltaic industry was not primarily a field of flourishing small business activity. Competing preferences for specific technological solutions to the Energy Crisis were often the result of competing problem perceptions within the loosely knit support coalition. A 1980 report by SERI that tried to give an overview of the various motivations for support in the field of solar energy found 49 motivational categories in politics and business and 78 in civil society, ranging from neo-mercantilist hopes and national security concerns to more general expectations about restoring individual self-determination.[32]

Measured against the hopes formulated at Cherry Hill, American photovoltaic commercialization went astray from the late 1970s. The expansion of manufacturing capacity went far slower than projected, growing incrementally from around 1.6 MW in 1978 to 7.8 MW in 1985. In comparison with catching-up European and Japanese manufacturers, the industry had lost much of its first-mover dynamic (see Figure 3). More important perhaps, many of the earlier developmental narratives about revolutionizing the American energy system via concerted industrialization over the following years lost their grip. When program manager Henry Brandhorst in 1984 looked at the remains of the 10-year commercialization programs, he suggested that "the magic of the market place" had made the consolidated industry "stronger and more vital." In addition, the failure of the early-day hopes to him meant a reaffirmation of an old common wisdom with respect to technology policy: "first you make a device efficient, then stable

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[30] "The Current State and Future Prospects of the U.S. Photovoltaics Industry." Hearings before the Subcommittee on Energy Development and Applications of the Committee on Science and Technology. U.S. House of Representatives, Ninety-Eighth Congress. Second Session 1984, 61, emphasis in the original.

[31] Jimmy Carter, Statement on Signing H.R. 12874 Into Law. November 4, 1978.

[32] Avraham Shama and Ken Jacobs. 1980. "Social Values and Solar Energy Policy: The Policy Maker and the Advocate." Golden, CO: Solar Energy Research Institute.

(if necessary), then low cost."[33] The mildly technocratic vision of doing it in the reverse order developed at Cherry Hill was severely discredited.

The final blow to the dynamic in the American photovoltaic sector had important macroscopic causes, namely in general policy changes and in changes of the overall salience of the energy issue. The Reagan administration gravely cut the budgets for renewables commercialization, dismantled significant parts of the earlier technology policies, and championed a reorganization of non-nuclear energy technology policies towards basic research. Asked for the reaction of the JPL developmental effort to the budget cuts, a program manager summarized that all "market development expenditures and associated commercial readiness targets have been deleted. In addition, all technical readiness goals have been dropped. In their place, a set of 'technical feasibility targets' limited to selected, high-risk PV components and processes will be substituted."[34] Rapidly declining oil prices since the early 1980s, the oil glut, in addition, rendered many of the initiatives of the 1970s temporarily obsolete.

These external shocks did, however, hit an already internally gridlocked commercialization regime. When interviewed by the *New York Times* (August 18, 1981) with regard to the Reagan administration's support cuts, key American manufacturers cherished the burial of the old commercialization regime. A Westinghouse representative promised:

> In the past, if a guy took out a piece of glass, poured some fluid on it, held it up to the sun and got some voltage off it, he made a headline and got some Government funds. Those days are over … It's time for big money commitments … If you were in it for the fun and excitement, it's time to get out.

Similarly, an oil representative stated:

> Letting some of the nonviable companies who depended entirely on Government grants run their natural course would be in our interest … It is hard to recognize the good products from the bad products, when the bad ones are getting intravenous feeding from the Government.

And finally, ARCO Solar's spokesman claimed that

> business executives, telecommunications companies, utilities, hydroelectric companies are going to start to see us more as a business now, not a hobby, not a ban-the-nukes/save-the-whales bunch of guys who stand around airports and pass out literature.

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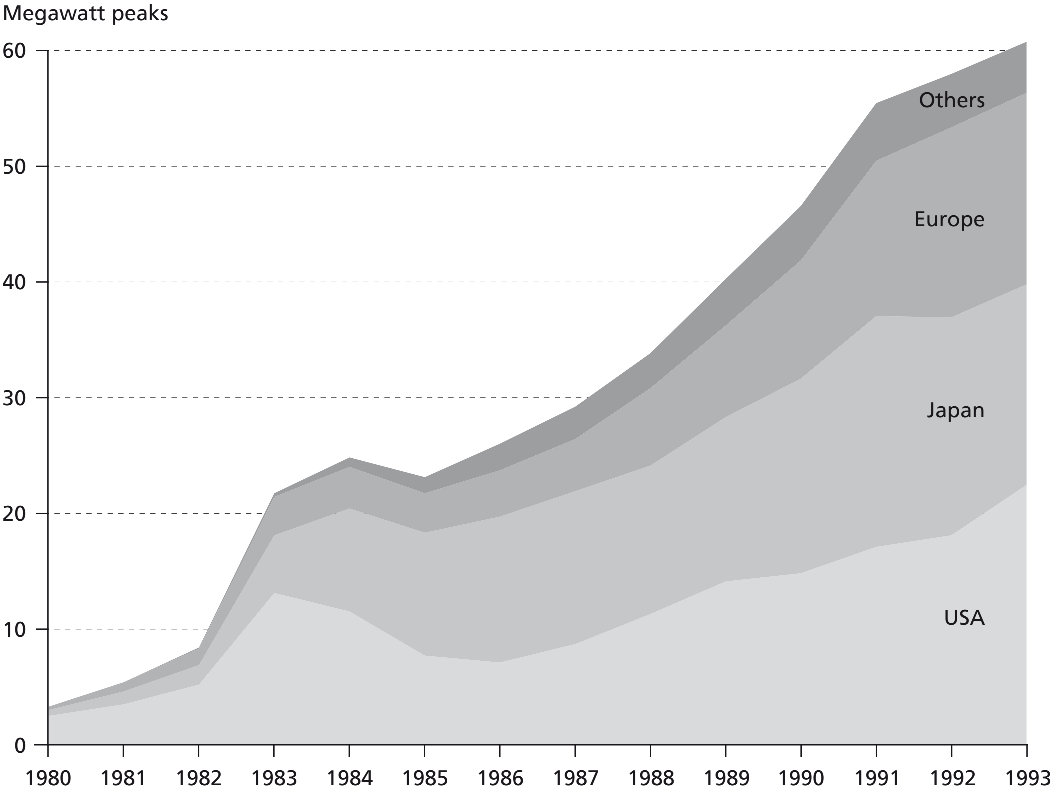
[33] Henry W. Brandhorst. 1984. "Photovoltaics – the Endless Spring." Conference paper. Seventeenth Photovoltaic Specialists Conference, Kissimmee, Florida, May 1–4, 1, 3.

[34] "Administration Budget Cuts in Conservation and Solar Programs." Hearings before the Subcommittee on Energy Conservation and Power of the Committee on Energy and Commerce. House of Representatives, Ninety-Seventh Congress. First Session 1981, 95.

Figure 3 Solar panel production in Europe, Japan, and the United States, 1980–1993



Source: US Office of Technology Assessment.

4 Conclusion

It took the American photovoltaic sector until the early 1990s to rediscover the 1970s' industrialization policies – then, however, overwhelmingly driven by international industrial competition and increasing frustration with failing climate change diplomacy, rather than by the old energy-focused coalitions. Still, all the motivational images, technological hopes, and coalitional possibilities for supporting photovoltaics resurfaced in various regions and political contexts from then on. The story of the early American solar industry can contribute to our understanding of technology policy in two ways. On the one hand, it illustrates the social conditions conducive to continuous technological development. On the other, it illuminates a process endangering continuous development in which concerted action via its successes may undermine cohesion and support over time.

In their comparison of the American and Danish wind industries in the 1970s and 1980s, Garud and Karnøe (2003) presented a surprising finding. Although much better equipped in terms of resources, American industry for a long time lost out against wind turbine manufacturers from Denmark. Their explanation mostly focused on different engineering cultures and traditions with respect to technological development. Their focus on *breakthroughs* took American manufacturers from one failed prototype to the next, while Danish engineers continuously improved "boring" yet operational designs (see also Heymann 1998). The 1970s' American photovoltaic sector had a similar problem, which, however, did not rest on cultural imprints. The continuous and coordinated development of the technology rested on the maintenance of outlays by a very heterogeneous support coalition which fragmented. At least by 1976, the expected effects of the commercialization programs loosely bound together leftist activists, oil concerns, high-tech firms, environmentalist politicians, and space administration officials. This support model was not interrupted by external shocks, technological obstacles, engineering mistakes, or the kind of disillusionment that often naturally follows high-hope movements. Instead, the sector failed at securing continuous outlays necessary for maintaining the initial dynamic and at sustaining a level of social cohesion necessary to hold together support institutions and individual groups' motivations.

The story of the solar industry can be understood as an illustration of Mark Mizruchi's above-cited argument about the negative coalitional effects of initial collective successes, as well as a suggestion for its extension. Why did the dynamic of the programs go astray exactly at the moment the sector had reached its goals to anchor itself in the ERDA complex and secure support for its development? The answer lies in the post-enactment politics of the support policies. The fulfillment of the coalition's initial plans to initiate a comprehensive public support program undermined the coalition's cohesion instead of keeping supporters on track, which in turn led to decreasing confidence in the technology's promised potentials. With the initiation of large-scale support measures the collective problem for supporters shifted from crafting an initial supporting coalition to securing concessions from participating groups. Failures to keep different interest groups committed falsified intermediary predictions, weakened the credibility of the developmental narrative, and revived uncertainties about the technology's medium-term potential.

This downfall of early American photovoltaic support suggests several directions that systematic research on technology policies could take in the future. In line with recent work on industrial and technology policy and the conceptual ideas laid out above (e.g., Block 2008; Schrank and Whitford 2009), one would be to shift the focus from questions of relative resource endowments, initial potentials for mobilization, and plain support motivations to questions of social organization over time. Furthermore, the more recent line of research on the network conditions of industrial and technology policy highlights that network failures have a critical political dimension. Fracturing sectoral relations do not just hamper industrial dynamics, but may have political effects in that they weaken the case for the maintenance or extension of supporting policies. The durable remaking of coalitions by the enactment of technology policies is then not just a function of timing, design, support generosity, and initial coalitional structures, but of political work to maintain sectoral cohesion.

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