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Beyond Technology Push vs. Demand Pull:

The Evolution of Solar Policy in the U.S., Germany and China

Centre for Sustainability Management

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ABSTRACT

To explain and promote the adoption of new technologies, researchers have debated the relative importance of technology push and demand pull factors (e.g., Schmookler, 1966; Mowery and Rosenberg, 1979; Peters et al, 2012). Here we examine a crucial problem of contemporary innovation policy — promoting the adoption of renewable energy to reduce anthropogenic global warming — that challenges prior models for large scale innovation adoption. From the recommendations of Mowery, Nelson and Martin (2010), we develop a typology of technology push and demand pull policy design principles for renewable energy adoption. We use these principles to analyze a sample of 79 solar energy policies from 1974 to 2011 in the U.S., Germany and China. To go beyond the push/pull dichotomy, we also map these policies to the (solar) value chain. From this, we suggest additions to the model of technology push and demand pull — distinguishing between direct and indirect push and pull — to explain the success of renewable energy policies.

Keywords: technology push, demand pull, technology policy, solar photovoltaic, renewable energy

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1 INTRODUCTION

A current example that has renewed this debate has been over policies to promote the deployment of renewable energies. While such policies are often justified in terms of economic development, the recent push has come due to increased concerns about global warming attributed to greenhouse gas emissions from fossil fuels (e.g. Hargadon, 2010). The challenge is particularly daunting because “The scale of this transformation dwarfs that of most prior problems of technology policymaking. Success requires the development, commercialization, and diffusion of many ‘suites’ of complementary energy technologies throughout society.” (Huberty and Zysman, 2010, p.1027)

In a special issue of Research Policy, three senior innovation scholars concluded that “strong governmental technology policy is an essential component of any portfolio of policies aiming to stop and reverse global warming” (Mowery, Nelson and Martin, 2010, p.1011). However, they argued that it is inappropriate to emulate previous technology-push approaches:

> *Halting or reversing global warming almost certainly cannot be achieved solely through ‘supply-side’ policies and the development of technological ‘solutions’. Indeed, one of the largest dangers created by the Manhattan or Apollo metaphor is that it may be adopted by politicians seeking to avoid the far more painful demand-side policies aimed at changing human behavior. … Public policies to support the development and deployment of technological solutions to global warming are urgently needed, but these programs must differ in design from the “big push” programs exemplified by the Manhattan or Apollo projects. (Mowery et al., 2010, p.1012)*

The adoption of solar energy is an example of the broader class of technology adoption problems that may depend on both technology push and demand pull factors. As with other forms of technological adoption, policies to encourage solar adoption have addressed both the technical risks (technology push) and overcome the objections of adopters (demand pull).

Here we review the prior research on innovation as it relates to the technology push vs. demand pull debate, as well as the issues that have been previously identified for the adoption of renewable energy (RE). We answer the call of Mowery, Nelson and Martin with what we believe is the first operationalization of their policy proscriptions, by using their analysis to develop an 18-point typology of push and pull policy design principles and conditions for RE adoption. We then use this to code longitudinal data on 79 solar photovoltaic (PV) policies from 1974-2011 for three major economies: U.S., Germany, and China.

From this, we suggest that the theoretical model of technology push vs. demand pull is incomplete in explaining the adoption of renewable energy in two ways. First, we suggest extensions to the often-studied direct approaches to technology push and demand pull are policies that indirectly achieve the same goals. Secondly, we identify the role of generic complementary assets as a crucial indirect technology push factor that should be considered in renewable energy and other innovation policies.

2 PUSH AND PULL FACTORS IN PROMOTING INNOVATION ADOPTION

The debate over the relative importance of technology push and demand pull dates back 50 years (Griliches and Schmookler, 1963; Schmookler, 1966; Mowery and Rosenberg, 1979; Scherer, 1982; Jaffe, 1988; Chidamer and Kon, 1994).1 Both have also been often used in policies promoting renewable energy (Loiter and Norberg-Bohm, 1999; Nemet, 1999).

Determining the relative importance of these two factors has two major implications. The first is the causal or explanatory, i.e. determining which factor is more important in explaining the successful (or failed) adoption of a new technology. Flowing from this is the second or normative dimension: what policies should a government adopt if it wishes to promote technological progress and the consumer (or producer) benefits that accrue from such adoption. While for decades the two camps argued for either the technology push or demand pull hypothesis, to date it is widely acknowledge that a more systemic perspective is necessary where both technology push and demand pull policies are important (Nemet, 2009; Mowery and Rosenberg, 1979; Sagar and van der Zwaan, 2006; Taylor, 2008).

2.1 Technology Push

The arguments for technology push contend that whether at the level of a specific inventor or firm (Abernathy and Clark, 1985) or at the aggregate level of an industry (Utterback, 1974), it is the rate of technological progress that determines the adoption and impact of new technologies. In most cases, the importance of industrial R&D is dependent on (or even subordinate to) the role of basic science in enabling this progress.

Perhaps the earliest advocate of this view was Schumpeter, who in his entrepreneurial (Mark I) and corporatist (Mark II) theories argued that radical and incremental innovation expand the base of technology which displaces existing technologies and firms. Some versions of this perspective adopt a weak form of technological determinism, assuming the direction (if not rate) of technological progress to be inevitable and perhaps even exogenous to the efforts of individual firms (Schumpeter, 1934, 1942; Nelson and Winter, 1982; Jaffe, 1988; Chidamer and Kon, 1994; Malerba and Orsenigo, 1996).

Some supporters of this perspective have made narrower arguments. On the one hand, the ability of a firm to deploy radical innovations may depend on a configuration of internal competencies to support a technology push approach (Abernathy and Clark, 1985). On the other hand, the interest of buyers in using a technology may depend on the cumulative incremental improvements in cost, features or quality (Mowery and Rosenberg, 1979). Still other researchers have examined the interdependencies within technology push. For example, Meyer (2000) concluded that within a technology push approach, technology can pull science or that science can push technology.

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[1] The debate tends to assume “a linear model of the innovation process with science at one end and markets or users at the other” (Chidamer and Kon, 1994, p. 95). For a rare exception, see the systems perspective of Edquist and Hommen (1999).

2.2 Demand Pull

The idea that new technologies are not endogenously created, but in fact are shaped by the nature of demand can be traced to the work of Jacob Schmookler (Griliches and Schmookler, 1963; Schmookler, 1966). As Scherer (1982, p.225) put it, "Schmookler's main contention, contrary to the prevailing emphasis on changes in scientific and technological knowledge, was that demand played a leading role in determining both the direction and magnitude of inventive activity." Schmookler (1966) and Scherer (1982) found that demand (as proxied by capital investment) led technical invention (as measured by patents).

In a review of 17 studies of innovation adoption, Utterback (1974, p.621) concluded:

> *Market factors appear to be the primary influence on innovation. From 60 to 80 percent of important innovations in a large number of fields have been in response to market demands and needs. The remainder have originated in response to new scientific or technological advances and opportunities.*

While studies of the impact of commercial or consumer demand on technological progress can inform public policy, a more direct link can be found in the role of government procurement. Edler and Georghiou (2007) discussed how EU governments could use public procurement to support national technology development and commercialization efforts.

In response to such studies, in their critique Mowery and Rosenberg (1979,p.105) argued that the role of demand was "overextended and misrepresented." Even at that early stage in the development of renewable energy, they concluded:

> *The point is that in certain areas, such as alternate energy or antipollution technologies, industries may simply lack sufficient R&D resources or the necessary market-generated incentives. (Mowery and Rosenberg, 1979, p.148)*

2.3 Push and Pull Factors in Promoting Renewable Energy

Both directly for renewable energy adoption and through analogous reasoning of successful U.S. and U.K. technology policies, Mowery et al. (2010) support the role of the national government in funding technology development to enable subsequent adoption. Technology push policies are also considered to be important for filling in the gaps in basic technological knowledge in the context of renewable energy (Mowery and Rosenberg, 1979).

However, there has been also a recent emphasis on the use of demand-side policies. For example, an official UK blue-ribbon commission argued that strict regulatory standards to mandate RE use would "stimulate innovation by reducing uncertainty for innovators" (Stern, 2007, p.452). Similarly, Hargadon (2010, p.1025) argued that "[d]emand-side policy incentives are considerably more effective at promoting the innovation and diffusion of renewable energy than R&D investments," a conclusion similar to that of an earlier study of other environmental technologies (Taylor et al., 2005). In his study of wind generation, Nemet (2009) found that demand-side policies made California the world's leading market for wind power in the 1970s and 1980s, but encouraged incremental over radical innovation. Peters et al. (2012) identified country-level spillover effects induced by demand pull policies.

Overall, studies on renewable energy adoption have suggested the need for a systemic approach by creating policies for both technology push and demand pull (Mowery et al., 2010; Peters et al., 2012; Taylor, 2008). However, only a few empirical studies on RE take such a systemic approach. One was Taylor (2008) who identified the importance of “interface improvement” in California solar policy as between the push and pull dichotomy Another is Peters et al. (2012) who focused on aggregate level of policy determinants without determining the effect of specific policy instruments. Our aim is to contribute to this research through a cross-country comparison of major RE markets applying a broad unit of analysis covering push and pull, and identifying a broader category of indirect push and pull policies.

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3 RESEARCH DESIGN

We are interested in the production and use of photovoltaic (PV) generating equipment — the direct conversion of solar energy into electricity — first made practical with the first silicon solar cell in the 1950s — which has been a major emphasis of RE policy and investment since the 1970s.2 We focus on three countries: the U.S., Germany and China, which have played a leading role in the deployment of solar energy. Based on the needs of its (government-funded) aerospace industry, United States was the technological leader and provided early niche markets from the 1960s until the 1990s. Through policy innovation, Germany has been the largest market in the world during the 21st century. Finally, with massive public investment in manufacturing companies at a time of credit contraction in the West, since 2009 China led the world in PV manufacturing capacity, as measured both by annual output and capital investment.

3.1 Data

The present paper is based on a secondary dataset of global renewable policies since 1974 that were compiled by the International Energy Agency (IEA) from 82 countries, including 28 IEA members and 54 other countries. The database contains nearly 1,000 policies with variables such as country, jurisdiction, year of implementation, policy status, policy type, objectives and a description. From the IEA database, we first selected all RE policies from our three countries (175 in total). Then, we selected only policies that directly relate to photovoltaic solar energy; this includes both solar-specific policies as well as broader RE policies which cover solar PV among other technologies. Overall, this narrowed the 175 RE policies to 79 policies: 49 U.S., 17 German, and 13 Chinese policies (). For comparability between countries, we coded only national policies (this also covers national policies being operationalized on the state level).

Country	Total RE Polices[1]	Relevant RE Policies[2]	Earliest Relevant RE Policy
U.S.	100	49	1974
Germany	41	17	1990
China	34	13	1996
Total	175	79	-

[1] All renewable energy policies in IEA database announced on or before December 2011.
[2] Includes all national policies that either are PV-specific policies, or are RE policies which include PV.

Table : Relevant policies from IEA database 1974-2011

The selection of the policy sample was subject to two major challenges: (1) comparability and (2) completeness. Regarding comparability, each entry in the IEA database could directly refer to an individual policy (e.g. U.S. "PURPA"), or to a larger "policy package" that covers many individual policies (e.g. U.S. "EPAct 2005"); such policy packages are

2 At the end of 2011, 94% of the world's supply of RE generated electricity came from hydroelectric, wind and solar PV (Ren21, 2012), but policies promoting RE adoption have de-emphasized hydroelectric because of limits on the availability of new generating sites.

particularly common in the U.S. To assure comparability, we coded only individual policies.[3] For complex packages, we consulted third-party documents (such as the text of the law) to verify and better understanding policy packages and the individual policies contained therein. Sometimes, this led to the identification of additional policies originally not described in the IEA description of the policy package, which we then added to our analysis for the sake of completeness.

In parallel to the IEA database, we developed from published sources (in the respective national languages) a chronological history of the major milestones of the solar policy in the three countries. We used these histories to supplement our analysis, but did not explicitly code events or policies outside the IEA data. For the U.S, this included Federal policies listed in the DSIRE database, various congressional reports, and reports from other research institutes (e.g., Cunningham and Roberts, 2011; Lazzari, 2008). For Germany, we used various German-language sources, mainly policy monitoring reports issued by ministries and research institutions as well as original policy documents such as legal texts and official program descriptions. For China, we supplemented the IEA database with Chinese government website information on solar policy as well as other relevant information obtained through limited interviews with government officials and professionals in the solar field.

3.2 Coding

Based on a historical analysis of U.S. and U.K. policies related to agricultural, biomedical and information technologies, Mowery, Nelson and Martin (hereafter MNM) made a series of recommendations for effective RE policies (Mowery et al., 2010, pp.1019-1022). Here we offer what we believe is the first effort to operationalize the MNM design principles for use in policy assessment. To operationalize and apply these principles to the empirical data of the IEA database, we developed a coding system for qualitative content analysis using an iterative process of coding and re-coding as recommended by Eisenhardt (1989).

Adapting the definitions of Edler and Georghiou (2007), we divided the MNM proscriptions into eight *technology push* (T1a[4],T1b,T1c,T1d,T2,T3,T4,T5) and five *demand pull* (D1,D2,D3,D4,D5) categories. A third category covered five principles that were *policy conditions* (C1,C2a,C2b,C3,C4,C5) that modify push or pull principles, such as long-term support (five years or more). Across these three categories, we identified 18 separate principles of the MNM policy proscriptions (Table 2; see also Appendix A.1).

[3] To code packages, we separated IEA entries representing policy packages into individual policies, using the database entry as the starting point to identify individual policies. Although we did not use the packages for coding, to assure transparency of data coding, in Tables A.2-A.4 we group the policies as reported in the IEA database.

[4] Although MNM does not explicitly call for public performance of publicly funded R&D, their earlier work has clearly supported government funding of public basic research (e.g. Mowery et al., 2004: 25-26; Salter & Martin, 2001). We thus interpret MNM as encouraging privately performed R&D in addition to publicly performed R&D, and thus use T1b and T1c for the former and T1a for the latter. Consistent with David (2004), we classify research by private universities and other non-profit organizations as “public.”

Group	Code	Policy design principle	Description and rationale
Technology push	**T**	**Funding technological research, development, and demonstration**	
	T1a	Public institutions performing publicly funded R&D	Public research institutions are important especially in basic research and in defining future research directions.
	T1b	Industry performing publicly funded R&D	Industrial firms are important in performing publicly funded R&D.
	T1c	Private investment in R&D	Funding should shift from public to private.
	T1d	No public funding of marginal improvement	Public spending should not support incremental improvements of existing technologies and instead focus on the technological frontiers.
	T2	Broad research availability	The result from publicly funded R&D should be broadly disseminated, and patents for upstream technologies discouraged or licensed at low cost.
	T3	Technology contests	Stimulate R&D efforts via rewarding technological achievements through prizes.
	T4	Technology demonstration	To demonstrate the feasibility of new technological designs R&D programs can include demonstration projects for early trial use.
	T5	Learning in use	Policies which connect adopters of technologies with manufacturers and R&D organizations to facilitate feedback of operating experience into the R&D process.
Demand pull	**D**	**Catalyze technological innovation by stimulating demand**	
	D1	Regulatory performance targets	Policies should drive demand towards alternative technologies through regulated performance targets.
	D2	Targeted financial incentives	Financial and fiscal instruments can be applied to encourage certain behavior, such as investments leading to early adopter or increased market demand.
	D3	Pricing emissions externalities	Policies should correct market prices for existing technologies (e.g., coal based power production) which do not reflect full social costs.
	D4	Government procurement	The diffusion of alternative energy technologies can be spurred by government procurement policies.
	D5	Public dissemination programs	Public information and dissemination programs to facilitate networking amongst various actors, such as (prospective) users and producers in order to spur adoption.
Conditions	**C**	**Characteristics of either supply or demand policies**	
	C1	Long-term support	A long-term perspective and stable and credible policy commitments (5+ years) are necessary for developing and improving alternative technologies and their adoption.
	C2a	Decentralized programs	Decentralization of policy programs spans diverse instances responsible for technology priority-setting, funding, and performance control.
	C2b	Centralized leadership	A centralized administrative structure sets overall priorities, monitors progress and evaluates performance.
	C3	Technological diversity	The energy-related technologies that are involved in any solution to global warming are extraordinarily diverse and will be developed and produced by firms in many different industrial sectors.
	C4	Global cooperation	Alternative energy technologies address a global problem but are applied locally; co-operation of national governments and even international subsidies are necessary to work on this global-local challenge.

See Appendix Table 5: A.1 for coding rules and more detailed explanations of each category.

Table : Coding push vs. pull policy proscriptions of Mowery, Nelson and Martin (2010)

We then coded each of the 79 policies as to whether they matched one or more of the 18 principles (as reported in Appendices A.2-A.4). We discussed our preliminary coding decisions to resolve ambiguity in the coding and assure consistent application of the coding rules. We used these discussions to revise the coding decisions, the coding rules or both.

Finally, to identify the importance of government policies in commercialization, we sought to identify the primary focus of each policy by the stage of the solar value chain that it addressed (Figure 1). Using an iterative approach, we refine our classification to six stages in the value chain: basic research, applied R&D, manufacturing, interface improvement, deployment, and use, as well as a seventh category (demonstrations) that may span one or more of these stages[5]. Table 3 shows examples of actors, activities and policies for each stage.

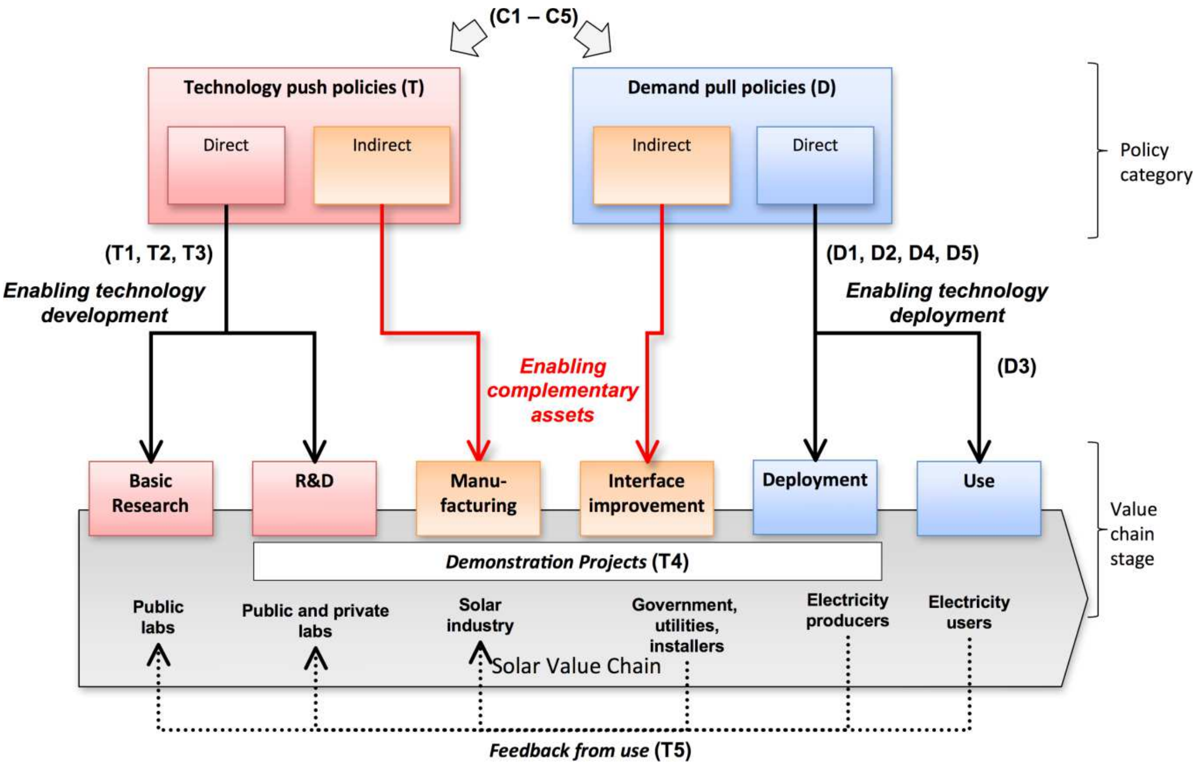

Figure : Solar value chain

[5] We classified manufacturing R&D as "R&D," limiting "manufacturing" to operation or scale-up. We reserved "Interface Improvement" for policies that bridged between the manufacturer and user (such as skilled installation; cf. Taylor, 2008) and also the resolution of adoption barriers such as technical interconnection, building codes or installation permits.

Value chain stage	Targeted actors	Types of policies	PV-related examples
Basic research	Science partners	Policies directed at encouraging basic research; often funding is provided for public research laboratories.	• New chemical formulas for solar cells
Applied R&D	Science partners, Industry	Policies funding research and development projects both for advancing technology and related manufacturing processes.	• More efficient solar panel/system
Manufacturing	Industry	Policies (which are not R&D) supporting competitive manufacturing and up-scaling.	• Subsidies for scaling up solar manufacturing • Provision of free solar workforce training
Interface improvement	Local government regulators, utilities, architects, installers	Policies for creating conditions and infrastructure that enable the subsequent deployment and use of technology.	• Providing regulatory basis (e.g. grid access) • Development of building codes for integrating solar technology • Streamlining permission/inspection procedures • Declaration of possible sites • Installer training
Deployment	Buyers of PV equipment	Policies incentivizing deployment of new technologies through financial incentives (grants, tax reductions, subsidized loans), technical assistance or education and outreach.	• Grants for procurement of solar panels • Feed-in-tariff for production of solar electricity
Use	End-users of electricity	As with deployment, encourages use of solar equipment, but focuses on end-users and applications in which technology is embedded or technology-related outputs are used.	• Diffusion of green power contracts which increase the use of green electricity
Demonstration	Science partners, industry, utilities, lead users	Polices facilitating the demonstration of the feasibility of new technological designs. Demonstration projects in this category focus on pre-commercial designs (e.g. demonstration plants, field trials, prototype development) for early trial use, rather than commercial demonstration projects used to encourage deployment.	• First time large-scale installation of new PV module (e.g. by a utility)

Table : Mapping policies to phases of the value chain

4 ANALYSIS OF THE POLICIES

4.1 United States

As the country that both invented PV and had the largest market, it is not surprising that the U.S. had the earliest and widest range of policies, including both push and pull policies.

4.1.1 Technology Push Policies

Although the U.S. government procured solar cells in the 1960s for satellites and other space applications, terrestrial solar policy has its roots in the 1973 oil embargo. One of the first policy responses of the U.S. government to the oil crisis was to dramatically increase funding for research and development activities (T1). This led to the enactment of the Solar Photovoltaic Energy Research, Development and Demonstration Act of 1974 (1974 Act), which created the first sizable research program for solar energy with expenditures of $1 Billion (plus another $1.5 Billion in the 1978 act) with a focus on basic research and broader R&D (42 USC §5581; 42 USC §5551). The act also created the Solar Energy Research Institute (SERI) which began operations in 1977 and became the National Renewable Energy Laboratory in 1991. Another research program of that time was the NASA-led Low-cost Silicon Solar Array (LSSA) project in which U.S. government spent $235 million from 1975-1986. Subsequently, since 1996, major research policies in solar has been administered by the Department of Energy under the umbrella name of Solar Energies Technologies Program (SETP) (later integrated in the SunShot Program), including such policies as the Solar America Initiative and Solar Decathlon. Most of these publicly funded R&D programs include both publicly performed (T1a) and private performed research (T1b).

Beginning in 2007, the Technology Commercialization Fund (TCF) aims to link research and development to commercialization by requiring matching private investments; other government programs also had matching requirements to encourage private investment (T1c) (cf. Jaffe et al., 2005, p.170). Subsequent research initiatives to promote radical innovation — such as Advanced Research Projects Agency–Energy (ARPA-E) and the Energy Frontier Research Centers — can be considered examples of the principle of “no public funding of marginal improvement” (T1d).

No policies studied explicitly provided for “broad research availability” (T2), although we believe that in most cases a policy of knowledge dissemination was implicit: any non-classified research performed at U.S. public labs is by law available to the public, while contract research (particularly by universities) tends to be published in open literature with acknowledgement to Federal funding. We found only one technology competition (T3), although the government used competitions to encourage improve capabilities further down the value chain, with programs such as the Solar Decathlon, “America’s Most Affordable Rooftop Solar” Competition, and the Solar America Cities awards.

U.S. policies for technology demonstration (T4) were part of either broader R&D programs (e.g. the 1974 Act) or larger policy packages addressing both push and pull (e.g. Solar America Initiative; Energy Independency & Security Act of 2007).

It was hard to find examples of learning in use (T5) that feed operational experience back to R&D. One of the few exceptions was the Solar Photovoltaic Energy Research, Development and Demonstration Act 1978:

> *"to select, as soon as he deems it feasible, a number of the applicants […] and enter into agreements with them for the design, purchase, fabrication, testing, installation, and demonstration of photovoltaic components and systems. Such selection shall be based on the need to obtain scientific, technological, and economic information from a variety of such systems under a variety of circumstances and conditions" (42 USC §5584; italics added).*

The ability of firms to supply technology depends on more than just doing R&D. So in addition to R&D support, policies supported firm efforts to develop manufacturing processes and capacity, either through financial incentives (e.g. Renewable Energy Innovation Manufacturing Partnership Program; Advanced Energy Credit for Manufacturers) or nonfinancial subsidies such as workforce training initiatives (e.g. Green Jobs Act). Although not corresponding to an MNM recommendation, about 12 percent of the US policies had such indirect technology push effects.

4.1.2 Demand Pull Policies

The U.S. lacks "Regulatory performance targets" (D1) at the national level, except for Federal RE government procurement goals based on executive orders (discussed below). However, beginning with Iowa in 1983, the Renewable Portfolio Standard (RPS) was implemented in the majority of states and established ambitious targets for RE to comprise up to 30 percent of electricity consumption by 2020 (C2ES, 2012); although state level policies, the widespread adoption has given RPS almost national significance, as evidenced by proposals for a federal RPS (Fischlein and Smith, 2013).

Instead, beginning with the Energy Policy and Conservation Act (EPCA) of 1975, the primary U.S. approach for incentivizing renewable energy (including solar) came with tax credits and other targeted financial incentives (D2) for equipment purchase and installation. The initial investment tax credits were provided both to residential and commercial buyers (e.g. Business Energy Tax Credits). The portfolio of tax incentives was further diversified through the EPAct 1992 which introduced the Production Tax Credit (PTC) which, instead of subsidizing equipment purchase, provided a subsidy for each kilowatt hour of RE generated. Also other programs introduced financial incentives such as grants via the Renewable Energy Production Incentive. Finally, the EPAct 2005 created a Loan Guarantee Program for Innovative Energy Technologies that became particularly important through the American Recovery and Reinvestment Act (ARRA) which appropriated $2.4 Billion in funds to cover $16 Billion in loan commitments (Brown, 2012, p.6f).

In proposing policies for “pricing externalities” (D3), MNM identified a long-standing concern by renewable energy supporters that the transaction price for fossil-fuels does not reflect the full social costs of such sources — including factors such as pollution and greenhouse gas emissions (CBO, 2012, p.8). A proposed carbon tax — the America’s Energy Security Trust Fund Act — was introduced in the Congress in 2007 and 2009 but never enacted. However, the price of fossil fuels were raised when oil and gas tax breaks were cut as part of the Energy Improvement and Extension Act of 2008 (Lazzari, 2008)

A commonly used category is government procurement (D4) which addresses the last two phases of the value chain depending on whether procurement covers technology equipment or actual electricity. Examples included the EPACT 2005, Solar Energy Research and Advancement Act, Solar America Initiative, and various presidential executive orders, but the magnitude of such procurement was relatively small compared to the U.S. energy industry.

Public dissemination programs (D5) are an established part of U.S. policies, usually not as a standalone activity but rather a complement to demonstration projects (T4) or financial incentives (D2). Exemplars are the Tribal Energy Program providing education and training for (potential) early adopters, and Solar Decathlon which enabled public visits of prototypes of developed energy systems.

4.1.3 Conditions

Perhaps the most important condition of the MNM framework, “long-term support” (C1) reveals a key weakness of U.S. solar policies and energy policies more broadly. Less than half of the policies were stable for five years or more, with the majority characterized by continued threat of phasing out, temporary extension, changes in eligible technologies, or changes in budget allocations. Many policies (such as ARRA) were enacted only for few years, with some be extended shortly before (or sometimes after) the planned phase-out, creating uncertainty for all parties involved. Another form of inconsistency can be seen in the Production Tax Credit (PTC) which covered solar photovoltaic technology only from 2004 to 2005. A third form of inconsistency has come with long-term policies that have only short-term budget allocations that need to be renewed every few years. Such policy inconsistency drove Luz International, the largest U.S. developer of solar farms, into bankruptcy in 1991 (West, 2011).

A further condition is decentralized programs (C2a) and centralized leadership (C2b). Here, U.S. policies can be characterized as split between purely federal administered (and thus central) leadership (C2b) and policies where federal governments leave it to the individual states to operationalize and monitor the programs (C2a, C2b). The former includes most of the energy tax credits (e.g. Residential Energy Tax Credit), while the latter includes the State Energy Program which provide federal funds to states to fulfill the program goals.

Most U.S. policies cover several renewable energy technologies and thus represent “technological diversity” (C3). However, early US policies focused explicitly on solar technologies (whether PV or including solar thermal) — particularly in the 1970s, which brought the Solar Photovoltaic Energy Research, Development and Demonstration Act. Except for the Solar America Initative and Solar Decathlon (all managed under DoE’s former

Solar Energy Technologies Program), most 21st century policies have been technology neutral. In fact, the Energy Policy Act of 2005 expanded eligible technologies from “renewable energy” to “clean energy” including nuclear, clean coal, and carbon capture and storage technologies;[6] while this further increases technology diversity, it could dilute the focus and resources available for RE.

Finally, policies have demonstrated global/international cooperation (C4). Early in U.S. support for renewable energies, the Solar Energy Research, Development, and Demonstration Act of 1978 created an “International Photovoltaic Program Plan” for “stimulating exports for United States manufacturers” which was administered by SERI (SERI, 1979, p.118). The successor organization, the National Renewable Energy Laboratory, pursued both bilateral and multilateral international activities (that included Germany and China), for instance to facilitate the development of solar standards. Going beyond export promotion, the Energy Independence & Security Act (EISA) of 2007 institutionalized mechanisms for international policy analysis, collaboration with foreign governments, and improved “energy diplomacy”.

4.2 Germany

While Germany pursued both push and pull policies, it is best known for its Feed-in-Tariff demand policy innovation, which encouraged private investment in RE generation equipment.

4.2.1 Technology Push Policies

The German interest in renewable energies emerged in the 1970s as a reaction to the oil crises and increasing concern about nuclear power (Wüstenhagen and Bilharz, 2006). The most important technology push policy for solar PV-related R&D identified in the IEA database is the Federal Government’s Energy Research Program. Implemented by different federal ministries (Ministry of Economics (BMWi); Environment (BMU); Agriculture; and Education and Research), it is a framework that sets priorities and provides funding for public and private research projects (T1a, T1b). Today, the government pays up to 50% of research costs under the Energy Research Program and companies have to match the public funds with own investments (T1c), while academic basic research is funded up to 100% (T1a). On average, PV received 32% of BMU spending for renewable energy research projects between 2004 and 2011. In 2011, this funding reached an all time high of €74 million (BMU, 2012).

The second major technology push policy has been government-funded research, particularly at the nonprofit Fraunhofer Institute for Solar Energy Systems (ISE), Europe’s largest solar research center. In 2011, 50% of its funding came from industry, 45% from EU and federal government project funds, and only 5% from permanent government funding (Fraunhofer ISE, 2012). Thus, Fraunhofer ISE made the shift from public to partly private

[6] Efforts have been made in the U.S. to reposition nuclear power as a “clean” technology (Garud et al., 2010), which could force traditional renewable energies to compete for subsidies and other policy support.

funding as recommended by MNM (T1c). It specialized in transferring the results from basic research and public-private R&D, e.g., through demonstration and learning-in-use activities (T4, T5). All R&D policies made reference to broad information dissemination programs to speed up the diffusion of research outcomes within the PV industry (T2). Policies promoting R&D contests (T3) were not found.

When coding push and pull policies, we found examples of hybrids. The 1,000 Roofs Solar Power Program of 1990 combined publicly funded and performed evaluation research (T1a) and subsidies for private, small-scale installations (up to 70% of the investment cost) (D2). The program served as a practical field test of the commonly available technology and generated valuable information that was fed back to R&D (T5). Users receiving subsidies were obliged to collect performance data for at least five years, which were then analyzed by Fraunhofer ISE; some of these early installations are still monitored today. These data collection and analysis efforts not only served as feedback to R&D, but were also published and broadly disseminated to inform potential users and other researchers (D5).

4.2.2 Demand Pull Policies

Germany's demand pull approach to supporting the deployment of PV technologies emphasizes financial incentives and subsidies from institutions such as BMWi and BMU, often involving the state-owned bank for economic development (Kreditanstalt für Wiederaufbau, KfW) (D2). Grants to support the purchase and installation of PV equipment were common in 1990s, with the 1,000 Roofs Program, the 100 Million Program and in part the 100,000 Roofs Solar Power Program. The other long-standing policy was through government-subsidized loans, which were available from the KfW since the 1990 Environment and Energy Saving Program (ERP) — and after 2009, under the new Renewable Energies Program.

However, the most important financial incentives for the deployment of PV equipment in Germany are regulated feed-in-tariffs (FiT) (D2). The Electricity Feed-In Law enacted in 1991 was the world's first FiT policy, and required grid operators to pay premium prices for green electricity supplied by producers of RE. Local utilities also introduced additional Full Cost Rates subsidies starting in 1993, but both the Electricity Feed-In Law and the Full Cost Rates were replaced by the Renewable Energy Sources Act (EEG) in 2000. Reflecting cost reductions due to learning effects, the EEG's tariffs are regularly reviewed with tariffs changed at least in seven out of the twelve years since 2000. PV tariffs were reduced several times in order to moderate the German PV boom. As an alternative, producers can sell their electricity directly to the market through different Green Power marketing instruments that allow producers to charge a price premium to cover additional costs of producing and distributing RE (D2). Since green direct marketing came up in the mid-1990s, federal and state-level ministries and public agencies increasingly purchase green electricity as a form of government procurement (D4).

Clear evidence for the last MNM demand pull category, public dissemination programs (D5), was found in at least two policies: the 1,000 Roofs Program directly targeted lead users and provided information on state-of-the-art PV technology, installation, and deployment on private buildings. The BMU's Climate Protection Investment program includes wide public communication on the possibilities of emission reductions which in some cases lead to sustainable energy concepts which integrate PV technology. As in the U.S., Germany did not adopt the policy principle of pricing externalities (D3) suggested by MNM.

The German demand pull policies related to PV covered the three final stages of the value chain (i.e. deployment and use), with the greatest emphasis (in policy and funding) for deployment of new solar panels. The database identified four policies supporting interface improvement, through codes regulating the modification of buildings and grounds for renewable energy purposes, as well as services such as architecture and engineering. Additionally, the Energy Industry Act and the EEG require that grid operators provide connections for RE generation. The final (use) stage has only recently gained support through a new EEG mechanism rewarding direct consumption of self-produced solar power.

4.2.3 Conditions

Regarding policy conditions in Germany, both the technology push and the demand pull policies are rather stable and long-term oriented (C1). The government has funded research at Fraunhofer ISE since 1981. On the demand side, while FiT and other policies are regularly amended, most have been in effect for a decade or more.

From an organizational viewpoint, Germany's federal PV policies are only in some cases based on decentralized structures (C2a), e.g., in the case of the 1,000 Roofs Program which was initiated and partially financed by a federal ministry, but implemented and co-financed by state ministries and agencies. A decentralized approach can also be found with government and nonprofit R&D funding. The dominant demand pull policy portfolio is instead based on centralized federal leadership (C2b) with policies such as the EEG initiated and controlled at the national level.

Technological diversity (C3) is commonly supported by German policies: in most cases, PV is part of a broader portfolio of technologies to provide sustainable energy and combat climate change. However, some policies were exceptions in focusing on or favoring PV, such as the 1,000 and 100,000 Roofs Programs, or the Full Cost Rates programs. The MNM condition of global cooperation (C4) was not identified in the database.

4.3 China

The Chinese PV industry is export driven, with about 90% of the industry outputs exported abroad.[7] The history of Chinese solar policies is a recent one with a rather limited set of policies implemented. Unlike in the U.S. and Germany, the initial emphasis was on demand pull before technology push. To be consistent with our earlier discussions on the two other countries, we will discuss technology push policies first.

[7] Interview with senior official, China Ministry of Science and Technology, May 27, 2011.

4.3.1 Technology Push Policies

Among the few Chinese technology push policies related to PV, the emphasis was on government-funded R&D (T1a, T1b). The national level strategic initiatives that can cover R&D support to PV industries include the national “973 plan” which focuses on basic research such as research on thin film battery (1997), national “863 plan” which focuses on advanced technology development and support the commercialization of PV technologies (1986), and national “key projects support plan” with funding available to research in PV technologies and its commercialization. The Renewable Energy Law amendments in 2009 initiated a Special Fund for renewable energy that will finance industry research and development (T1b). The two other policies that foster technology development in renewable energy include the Medium and Long Term Development Plan for Renewable Energy (2007) and the International Science and Technology Cooperation Programme for New and Renewable Energy (2008) (T1a, T1b).

Among the relevant policies listed in the IEA database, we found that only the 2006 Renewable Energy Law and its amendments in 2009 addressed broad knowledge dissemination (T2), the International Science and Technology Cooperation Programme mentioned technology contests (T3). No evidence of technology demonstration (T4) or learning in use (T5) was found.

4.3.2 Demand Pull Policies

Most of the demand pull policies in China fall in our categories of regulatory performance targets (D1) and targeted financial incentives (D2), with many recent policies focusing on D2.

The history of the regulatory performance targets (D1) related solar policies goes back the earliest RE policy seen in China: the Brightness Programme. Started in 1996, this program sought to electrify towns and villages in remote areas by using wind, solar and other renewable energy sources, and remains in effect today. Only in 2003 did China create preferential tax policies to encourage foreign investment into RE enterprises and thus to source foreign knowledge on production and installation. This was the first policy to use targeted financial incentives (D2), offering income tax cuts for the producers and consumers of renewable energy, as well as a reduction of the import tax for “green” equipment. Later on, most policies used financial incentives, such that 11 of the 13 policies cited from the IEA database fall in the D2 category.

The first overarching policy for encouraging domestic demand for RE did not come into place until 2006. It was the Renewable Energy Law (2006) by which RE became the preferential area for energy development. Therefore grid access was guaranteed (i.e. interface improvement) and national targets for energy production from RE sources were set (D1). At the same time, this policy was the starting point for very dynamic RE policy development in China. One year later (2007) the National Climate Change Programme set an energy efficiency objective of reducing energy consumption per unit of GDP by 20% by 2010 and of quadrupling GDP between 2000 and 2020 while only doubling energy use, for combating climate change (D1). The government took measures to close small, less efficient industrial facilities in sectors including iron and steel, cement, aluminum, copper, glass or ceramics.

All output from renewable power generation projects can be sold at guaranteed prices to the grid company, where prices will be determined by the price authorities of the State Council. Grid operators will be able to recover extra costs associated with this regime through their own selling prices (D3). Still in the same year — as a consequence of the program — the government set medium and long-term goals for capacity installation for each RE technology: solar PV 1.8 GW; hydro 300GW (D1). In 2009 the renewable energy law was modified with adjusted premiums and additional research programmers in off-grid RE solutions.

Since 2008, the national and provincial governments established various programs to stimulate RE adoption through financial incentives (D2), such as the national level Solar Power Roof Plan in March 2009.

The Golden Sun Programme was proposed in July 2009, with a goal of 600MW of installed solar PV capacity across China. The program has provided grants both at national and provincial levels to subsidize capacity installation and preferential electricity tariffs (D2), and includes demonstration projects to disseminate knowledge about existing technologies (D5). For these projects, the central government subsidizes up to 50% (on-grid) or 70% (off-grid) of the entire installation costs and requires that electricity utilities in the area purchase the extra capacity generated by the project at unit price similar to power generated from other sources (such as coal). The Chinese government at both national and provincial levels has extensively used demonstration project (D5) as demand pull, such as the Brightness Programme, and the Golden Sun Programme.

In 2011, the central government considered a feed-in-tariff to set the price of electricity generated by sun power at 1.09 yuan/kWh; although 3 times as expensive as power generated by coal, it was still not enough to allow Chinese manufacturers to sell their equipment domestically at a profit (Zhang, 2010). In 2011, the Solar PV Feed-in-tariff Policy took effect (D2) for solar PV projects (approved before July 2011 and put in operation within the same year) with a 1.15 yuan/kWh tariff (18 USD cent equivalent) .

4.3.3 Conditions

The majority of Chinese PV policies emphasized both centralized leadership (C2b) and decentralized implementation of PV programs (C2a). With a strong planned economy in history and a powerful central government in place, it is also common to see some of the policies aim for a long term (C1) such as the Medium and Long Term Development Plan for Renewable Energy, the National Climate Change Program, and Renewable Energy Law. In addition, eight out of the fourteen polices cited in the database mention technology diversity (C3), suggesting the determination of the Chinese government in promoting a range of renewable energy approaches. For global cooperation (C4), the International Science and Technology Cooperation Programme for New and Renewable Energy in 2008 sought to boost technological development, introduce cutting-edge technologies in the national market, attract overseas scientists and develop exchange programs with international research centers.

5 ANALYSIS

5.1 Commonalities of Policy Choices

In Table 3 we summarize the prevalence of the various MNM policy principles and the associated value chain stages from the IEA data for the three countries.

Codes			U.S		Germany		China		All		
Group	**Code**	**Policy**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**Mean[1]**
Technology push	T1a	Publicly funded public R&D	11	22%	4	24%	5	38%	20	25%	28.1%
	T1b	Publicly funded private R&D	11	22%	3	18%	5	38%	19	24%	26.2%
	T1c	Private investment in R&D	6	12%	3	18%	0	0%	9	11%	10.0%
	T1d	No public funding of marginal improvement	4	8%	0	0%	0	0%	4	5%	2.7%
	T2	Broad knowledge dissemination	0	0%	3	18%	3	23%	6	8%	13.6%
	T3	Prize competition	1	2%	0	0%	1	8%	2	3%	3.2%
	T4	Demonstration projects	9	18%	3	18%	0	0%	12	15%	12.0%
	T5	Learning in use	0	0%	4	24%	0	0%	4	5%	7.8%
Demand pull	D1	Regulatory performance targets	1	2%	6	35%	6	46%	13	16%	27.8%
	D2	Targetedfinancialincentives	17	35%	12	71%	9	69%	38	48%	58.2%
	D3	Pricing externalities	1	2%	0	0%	2	15%	3	4%	5.8%
	D4	Government procurement	9	18%	1	6%	0	0%	10	13%	8.1%
	D5	Public dissemination programs	15	31%	2	12%	3	23%	20	25%	21.8%
Conditions	C1	Long-term support	18	37%	13	76%	5	38%	36	46%	50.6%
	C2a	Decentralized authority	18	37%	6	35%	9	69%	33	42%	47.1%
	C2b	Centralized leadership	47	96%	13	76%	9	69%	69	87%	80.5%
	C3	Technological diversity	37	76%	12	71%	7	54%	56	71%	66.6%
	C4	International cooperation	3	6%	0	0%	3	23%	6	8%	9.7%
Value chain	Basic	Basic research	4	8%	3	18%	2	15%	9	11%	13.7%
	R&D	Research and development	10	20%	4	24%	4	31%	18	23%	24.9%
	Manu-facturing	Manufacturing	6	12%	0	0%	2	15%	8	10%	9.2%
	Demo	Demonstration	11	22%	4	24%	1	8%	16	20%	17.9%
	Interface	Interface improvement	15	31%	3	18%	5	38%	23	29%	28.9%
	Deploy	Deployment	29	59%	11	65%	12	92%	52	66%	72.1%
	Use	Use	7	14%	2	12%	4	31%	13	16%	18.9%
Push vs. Pull		Push only	11	22%	3	18%	1	8%	15	19%	15.9%
		Pull only	31	63%	13	76%	7	54%	51	65%	64.5%
		Both push and pull	7	14%	1	6%	5	38%	13	16%	19.5%
		Total	49		17		13		79		

[1] The unweighted mean of the three country ratios.

Table : Descriptive coding statistics of three country samples

Each country differed in their mix of push and pull strategies:

- Germany emphasized pull very early and throughout, but later added a limited number of push policies. However, the expenditures for pull policies are the largest within Germany, and the largest pull expenditures among all three countries.
- While the U.S.'s initial policies included both push and pull, new policies emphasized pull until the mid-1990s, and then most policies combined push and pull elements.[8]
- China's formal (IEA) policies favor pull, with technology push largely absent from later policies. However, those announced policies do not acknowledge China's sizable supply push investments in manufacturing, as discussed below.

In the average across all countries, the MNM technology push policy most commonly used is the provision for *publicly performed R&D* (T1a) — although not explicitly identified by MNM — and *public funding of private R&D* (T1b) with 28 percent and 26 percent, respectively; T1a and T1b are also the most consistent push policies across the countries. Several categories were difficult to measure from the policy database, such as the use of public funding for private R&D and the MNM ban on *funding marginal improvements* (T1c), while our database of public policies only identified *private R&D funding* (T1b) when it was a condition of receiving public funds.

On the demand side, the most common policies are *financial incentives* (D2) used on average 58.2% of the time — although each country used a different form: tax credits in the U.S., a feed-in-tariff for Germany and a mixture of incentives in China.[9] Both China and the U.S. made use of *regulatory performance targets* (D1)(i.e. RE power quotas), and the U.S. also frequently used *government procurement* (D4). Overall, the U.S. had the most policies and used the broadest range of approaches over the longest period of time.

In terms of conditions, all three countries had policies that combined *decentralized authority* (C2a) and *centralized leadership* (C2b) — possibly reflecting the size of the respective national economies (#1, #2 and #4). The countries also used a mix of solar-specific and *technology neutral* (C3) policies. However, *long-term support* (C1) was the majority of policies only in Germany — which may relate to differences in the political economy, a broader societal support for RE policies, or the specifics of the U.S. (with its reliance on temporary tax credits) or China (with its relatively recent interest in RE).

What was largely or entirely missing from the policies of all three countries?

- *Prizes* (T3): only one prize competition each in the U.S. and China.
- *Pricing externalities* (D3): as was known to MNM, proposals for a "carbon tax" and other such approaches have been proposed but have proven highly controversial.[10]
- *Global cooperation* (C4): was rare in the U.S. and China and non-existent in

[8] Jaffe et al (2005) looks at the proposed 2004 U.S. budget related to GHG reduction and finds the push/pull numbers to be comparable ($1.3 vs 1.0 billion); within RE-specific policies, there's a slight bias towards R&D over pull policies ($430 vs. $300 million).

[9] In the U.S., subsidized loans to manufacturers were used starting with the 2009 ARRA, but it's too soon to say whether this is an ongoing policy shift or a one-time intervention.

[10] California has announced its own cap-and-trade policy and the European Union has announced an Emissions Tracking Scheme, but both would take effect in 2013.

Germany. We believe that the IEA database accurately reflects each government's tension between economic development and fighting global warming — and thus the general lack of effective global collaboration advocated by MNM — but the data might also omit such collaboration if these policies are enacted through bilateral political negotiations.

In some cases, individual laws combined both push and pull elements, as with the U.S. Solar America Initiative (2006). In other cases, omnibus laws combined a wide range of unrelated policies, as with China's 2007 Climate Change Program or the U.S. American Recovery and Reinvestment Act (2009).

Finally, we found two categories of policies that were not articulated in MNM typology:

- Non-technological "push" policies (i.e. *indirect* technology push): efforts to supply finance, skilled labor or other non-tech supply push factors directly supporting manufacturing appear to be overlooked in the MNM framework.
- Policies improving the interface between supply and demand (i.e. *indirect* demand pull): a central government promoting renewable energy would also want to reduce the likelihood that local circumstances (such as missing infrastructure, building permits or skilled installers) would discourage adoption.

Both the MNM recommendations and the policies enacted in the three countries were distributed across the solar value chain. Most (or in China, nearly all) policies emphasized deployment, i.e. the purchase and installation of solar generating equipment. On the upstream part of the value chain, applied R&D was favored over basic research or manufacturing. Each country also demonstrated increasing policy sophistication over time as the limitations of previous policies became known.

5.2 Policy Outcomes

The IEA database does not include policy outcomes, but from other data we could broadly assess the country-level success of each country's policy efforts — both in ramping up the supply of PV equipment and winning adoption of such equipment to generate electricity.

The U.S. was the early leader in developing PV technology from the 1960s to the 1980s, but adoption was relatively slow due to high prices and inconsistent policy support. In the 21st century, both public and private R&D investment focused on thin film solar technologies (where U.S. firms were deploying new patented technologies), such technologies have been losing global market share since a 2009 peak of 19%, as crystalline silicon cell prices continued their dramatic price cuts (Green, 2005; West, 2011; Wang, 2012).

Meanwhile, Germany's innovative demand pull (feed-in-tariff) policy provided guaranteed funding by electricity customers to assure a predictable rate of return, with spending that totaled €29 billion from 2006-2012. Germany was also distinguished by consistent increases in adoption each year, as compared to other European countries (such as Spain, Czechoslovakia and Italy) that adopted temporary policies that catapulted them into the top ranks of adopters one year, and back to irrelevance later on (Wüstenhagen and Bilharz, 2006; Ren21, 2012; BDEW, 2012).

The Chinese policies were relatively late and (as according to the IEA database) limited in scope. However, through rapid expansion of manufacturing capacity from 2005-2011, China became the world's leading producer of PV equipment: in 2009, First Solar of the U.S. was the first solar manufacturer to ship one gigawatts of capacity in a single year, but by 2011 four Chinese firms had done so. China benefited from country-level spillovers due to demand pull policies in other countries, particularly Germany (Peters et al., 2012). Chinese manufacturers were able to rapidly scale up through financing through government banks in the form of loans, loan guarantees and line of credit, which of course also represents a technology push measure (Edler, Georghiou, 2007). By one estimate, global venture capital in solar totaled $1.7 billion in 2010, but Chinese government banks financed $34 billion in debt that year, including $8.9 billion to LDK Solar from the China Development Bank (Osborne, 2011).[11] Such policies were not reported in the IEA database, and in fact were not openly discussed by the Chinese government.

Overall, these policies brought global installed capacity of PV equipment to 70 gigawatts at the end of 2011, with Germany accounting for 35% (Ren21, 2012). Fueled by German demand, the rapid growth and scale economies of Chinese manufacturers brought a rapid decline in the cost of PV equipment from 2010-2012 — leading to bankruptcy by PV producers unable to quickly scale up and reduce costs, both in the U.S. (Abound, Evergreen, Solyndra, SpectraWatt) and Germany (Q-Cells, Solon). In response, in 2011 Solar World AG — based in Germany but with U.S. manufacturing operations — filed an unfair trade complaint with the U.S. International Trade Commission, which in 2012 led to U.S. tariffs of up to 36% on Chinese imports.

[11]The single year investment of $34 billion in 2010 compares to $31.2 billion in combined (depreciated) plant property and equipment for Intel and TSMC, the world's largest semiconductor manufacturers.

6 DISCUSSION

This paper answers the call of Mowery, Nelson and Martin (2010) and others in *Research Policy* for an improved understanding of how innovation policy can be used to redirect economic activity to combat manmade global warming. It does so by operationalizing and applying MNM's proscriptions to provide the first in-depth analysis of the national solar policies in three leading markets — U.S., Germany, and China — that extend our understanding of solar industry dynamics and climate change policy more broadly. Finally, it contributes to the literature on the role of technology push and demand pull policies in promoting renewable energy — and innovation adoption more generally — while highlighting the importance of indirect push and pull policies in the adoption of systemic innovations.

6.1 Applying Mowery, Nelson and Martin to the Solar Industry

We developed the first operationalization of the MNM framework by mapping their call into 18 policy principles, and then applied these principles to code 79 solar-related policies from the IEA database from 1974-2011 for the U.S. (the first market for photovoltaic power), Germany (today the largest market) and China (today the largest producer of PV equipment).

The IEA data shows that the most common policy instruments are demand pull, particularly targeted financial incentives (D2) — which are more than twice as common as the most common tech push policies, those for publicly funded R&D (T1a, T1b). Among the MNM conditions, the most common were centralized control (C2b) and technological diversity (C3). Within the value chain, most policies focused on deployment of solar generating equipment.

Actual policies lagged MNM's recommendations (as they were likely aware) in several areas, including broad knowledge dissemination (T2), pricing externalities (D3) and international cooperation (C4). They predicted success would come when "private investments in energy R&D [exceeded] public investments" (Mowery et al., 2010, p.1020) which has been true in the U.S. However, it was not true in Germany (where ratepayer funding through the FiT drove investment) or in China (where government banks funded manufacturing); both Germany and China countries appear to have been more successful than the U.S. on pull or push policies (respectively), consistent with Hargadon and Kenney's (2012) observations about the limitations of private funding for RE investments.

6.2 Challenges of Push and Pull Policies in Renewable Energy

The greenhouse gas reductions from renewable energy come from the installation and use of RE generating equipment. The key driver for adoption of such equipment is stimulating early demand to prime the experience curve and thus create a virtuous cycle of falling prices and increasing adoption (Neij, 1997). Selecting a policy to "prime the pump" of this virtuous cycle intersects the broader debate about the efficacy of technology push and demand pull policies.

Demand pull policies for environmental technologies cause more public benefit through their use (Taylor, 2008) and are more effective in promoting renewable energy (Hargadon, 2010). However, push policies are often required to promote radical innovation (Abernathy and Clark 1985) while pull policies can bias innovators towards incremental innovation (Nemet, 2009). Nemet (2009) concluded such incrementalism contributed to the limited success of demand policies in promoting adoption of wind power in California from 1975-1991. Consistent with MNM's call for avoiding funding marginal improvements (T1d), many of the U.S. PV R&D investments of the 21st century emphasized major breakthroughs, particularly in thin film PV.

When compared to Nemet, our study of solar across three countries suggests that solar adoption was driven not by dramatic radical breakthroughs, but through the accumulated incremental improvements from 1974-2011. For manufactured components such as solar panels, efforts to stimulate demand — particularly the German feed-in-tariff — grew the market, allowed for learning and scale effects, attracted new entry and led to relentless cost pressures — not only in Germany, but due to country-level spillovers also in China and the U.S. (Peters et al., 2012). The result of demand stimulation was a steady cost reduction in panel costs over 30 years — a 22% cost reduction for every doubling of the industry's cumulative panel production (IRENA, 2012). Meanwhile, this market growth and competition incentivized decentralized cost reduction in the "Balance of System" (non-solar panel components) as suppliers and installers addressed each "reverse salient" of cost barriers as they arose (cf. Hughes, 1989). Non-standard solar technologies (such as Solyndra's thin film tubes) were unable to benefit from this cost reduction.

While such incremental improvements cut panel prices more than ten-fold over three decades, the private investments necessary to achieve scale economies required a long-term consistency that was notably present in the German policies and lacking in key U.S. ones (China's RE policies being too recent to provide a clear picture) (see also Lüthi, 2010). The predictability of FiT returns also overcame a key uncertainty deterring RE investment — weighing the long-term price of traditional energy against known short-term RE capital costs (cf, Jaffe et al., 2002).

The policies of these three countries also highlight the importance of indirect measures supporting technology push and demand pull. On the push side, new technologies cannot make it into practice unless they are produced, which turns out to be a crucial bottleneck for a high-volume price-sensitive market such as energy; all three countries provided support to help domestic manufacturing (and thus domestic job growth) though at different point of times and with different amplitude. On the pull side, the interface between manufacturers and eventual buyers can help or hurt the adoption process: for solar panels, key issues include local government regulation, distribution, skilled installers and financing. Such interface improvements increase the rate of adoption of solar equipment in a given economy, but not necessarily sales of domestic producers.

6.3 Role of Infrastructure and other Assets in Innovation Adoption

Beyond traditional technology push and buyer pull, Taylor (2008) identified the importance of improving the interface between producers and buyers. Improvements to such interfaces — which remove barriers to adoption by buyers and thus stimulate buyer demand — accounted for nearly a third of U.S. policies in our study (more in China, less in Germany).

Such interface improvements — whether reducing regulatory barriers to adoption or increasing availability of skilled installation staff — apply beyond the solar industry of our study (and Taylor's) to broader challenges of distributed production of renewable energy. This suggests links to two earlier literatures — the role of infrastructure in adoption of systemic innovation, and the producer's need to attract both end-users and co-specialized complementary assets such as installers.

Systemic innovation requires the careful coordination of many design, production and deployment decisions to make sure that the various elements of the system are available simultaneously, and are subject to a wide range of unanticipated or unintentional interactions (Bergek et al, 2008). A common requirement for adoption of such innovations is the deployment of an infrastructure that enables adoption of the end technology (Hargadon and Douglas, 2001; Maula et al 2006). Examples of such infrastructure might include not only installers for distributed solar power systems, but charging/fueling stations for electric or hydrogen cars (MacKenzie, 1994).

This corresponds to the more general problem of attracting a supply of specialized complementary assets (Teece, 1986) — which both require and are required by adoption of the end product — whether installers and solar panels or (as in Anderson and Parker, 2013) storage to supplement intermittent RE power generation. The producers thus face the challenge of attracting both parties of a two-sided market (cf. Evans, 2003) — in this case, both infrastructure (installers) and buyers of the end product (panels). As with any such two-sided market, producers must either attract third-party investment to create such infrastructure in anticipation of buyers, or fund the creation of such infrastructure themselves. Although this would increase capital requirements, a few firms (such as the largest US producer, First Solar) developed such end-to-end integration to assure the availability of such assets and reduce obstacles to deployment.

6.4 Limitation and Future Research

Our sample had important limitations. We didn't measure subnational policies for U.S. or German states, nor supranational policies (e.g., the EU). While providing commensurable data across three countries, inferences about policy prevalence (particularly for China) are based on small numbers. Due to incomplete data, we can't measure the financial magnitude of all the policies and (beyond adoption) lack outcome measures for their respective efficacy.

As MNM note, the challenges of transforming national energy policies to address global warming are daunting. Future research might extend the application of MNM's recommendations (and this coding scheme) to other renewable energy technologies in other geographic contexts. It might also examine some of the desirable but rare aspects of their recommendations, particularly global cooperation which as MNM (and Peters et al., 2012) note, is essential to link national jurisdictions to address a global environmental challenge. Meanwhile, the context of renewable energy adoption offers a series of large-scale quasi-experiments to consider the relative contribution of push and pull policies — not only the direct effects previously theorized, but indirect factors that link technology supply to user demand.

Finally, of particular interest to *Research Policy* readers, there is a dearth of empirical and theoretical literature on the diffusion and adoption of systemic innovations. While researchers have examined telecommunications, digital networks, energy and banking, a broader perspective (building on that for complementary assets and two-sided markets) is needed to explain the more general processes of creating and promoting adoption for a complex system. While general economic (e.g. Antonelli, 2001) and sociotechnical (Lyytinen and Newman, 2008) models of systemic innovation have been proposed, they have not been linked to empirical studies of how actual systems are conceptualized, designed, developed, produced and adopted.

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8 APPENDIX A

Code	Policy design principle	Description and rationale	Exemplary statements from MNM	Qualitative indicators (proxies)
T	**TECHNOLOGY PUSH: Funding technological research, development, and demonstration**			
T1a	*Public institutions performing publicly funded R&D*	Public research institutions are important especially in basic research and in defining future research directions.	Note: This principle results from MNM's statements on research performed by industry (see T1b). In consequence, even if the share of industrial research increases, public institutions performing (basic) R&D remain.	Public budgets allocated to universities or public research institutions; e.g., to researchers at national or local agencies, competence centers (e.g., German Helmholtz Centers, U.S. National Research Laboratories)
T1b	*Industry performing publicly funded R&D*	Industrial firms are important in performing publicly funded R&D.	"… a significant portion of government R&D funding for the development of climate-friendly energy technologies is likely to support R&D performed by industrial firms. Industry will play an especially important role as a performer of publicly funded R&D in prototype development and testing." (p. 1020)	Public budgets allocated to private research; e.g., funding corporate R&D, private research centers, industrial technology clusters
T1c	*Private investment in R&D*	Funding should shift from public to private.	"… public R&D investments in the development of new energy technologies must be complemented by private investments in energy R&D; indeed, if the initiative is to be successful, private investments in energy R&D are likely to exceed public investments." (p. 1020)	Public funding stimulates or even obliges private spending for R&D; e.g., through matching schemes
T1d	*No public funding of marginal improve-ment*	Public spending should not support incremental improvements of existing technologies and instead focus on the technological frontiers.	"… established firms or user groups are able to exert a dominant influence over the agenda of public R&D programs … [and] are likely to focus on near-term improvements in existing technologies. [But] public funding for marginal improvements of existing technologies is misdirected. Instead, public support should focus on advancing the technological frontiers." (p. 1021)	1.) Policy supports basic research and "big leaps" with an obvious distance to commercialization *or* 2.) Policy does not support technologies on the market or nearly ready for the market
T2	*Broad research availability*	The result from publicly funded R&D should be broadly disseminated, and patents for upstream technologies should be discouraged or licensed at low cost.	"[S]ocial returns to R&D … are likely to be greater when those results are broadly available… [G]overnments [should] structure their R&D programs to support and encourage broad dissemination of the scientific and technological knowledge produced by their R&D investments … [P]atenting should be reserved for results that are close to practical application and that patenting of research results whose use is primarily as an input to further research should be minimized."(p. 1020)	1.) Existence of measures to require or enable dissemination of public or private R&D results; e.g., through dedicated communication infrastructure, funding for dissemination *or* 2.) Patenting rules must avoid exclusivity in case of basic R&D results or discourage exclusive patent licensing in case of basic R&D results
T3	*Technology contests*	Stimulate R&D efforts by means of rewarding technological achievements through prizes.	"Prizes … have been recommended as a complement to other instruments of government policy, including public R&D funding, in supporting the development of climate-friendly energy technologies. Prizes are best-suited to the 'technological breakthrough' characterization of innovation …" (p. 1021)	Existence of publicly initiated contests for technological achievements; criteria are e.g. newness, breakthrough potential; prizes can be awards, contracts; achievements may cover both technological breakthrough as well as broader systems development

Code	Policy design principle	Description and rationale	Exemplary statements from MNM	Qualitative indicators (proxies)
T4	Technology demonstra-tion	To demonstrate the feasibility of new technological designs R&D programs can include demonstration projects for early trial use.	"Demonstration projects provide a bridge between R&D and use of a technology in the environment of actual practice … As such, demonstration projects can provide important information for future R&D investment … We believe that effective public programs … should also include mechanisms for the support and encouragement of early trial use of new technologies …" (p. 1021)	Support of prototype development and demonstration aiming at early trial use experiences; e.g., demonstration plants, field trials, prototype development
T5	Learning in use	Policies which connect adopters of technologies with manufacturers and R&D organizations in order to facilitate feedback of operating experience into the R&D process.	"… learning in use also means that broader adoption and more extensive operating experience will feed back into improvements in these alternative-energy technologies … These closely linked processes of adoption and technological improvement may benefit from public information dissemination programs that link early adopters with one another and with major producers and R&D …" (p. 1013)	Existence of dissemination mechanisms that facilitate exchange between adopters/users with manufacturers and/or R&D organizations
D	**DEMAND PULL: Catalyze technological innovation by stimulating initial and increased demand**			
D1	Regulatory perfor-mance targets	Policies should drive demand towards alternative technologies through regulated performance targets.	"Specific regulatory requirements (e.g. emission or performance targets) or targeted financial incentives (tax credits), may spur the adoption of specific technologies … Supportive price and regulatory policies can significantly enhance the effectiveness of government R&D programs in this area." (p. 1020)	1.) Existence of national (state- or other level) performance targets; e.g., in terms of renewable energy production or CO_2-reductions *or* 2.) Existence of targets either on the technology or the user level; e.g., quotas of renewable energy usage, CO_2 emissions, but also performance in terms of technology costs
D2	Targeted financial incentives	Financial and fiscal instruments can be applied to encourage certain behavior, such as investments, that leads to early adopter or increased market demand.	"… the early versions of most alternative energy technologies would be handicapped in direct comparisons with existing technologies … the adoption of the initial versions of more environmentally friendly technologies may require subsidies or other forms of public support for early adopters of these technologies." (p. 1013)	Existence of financial (e.g. preferential loans, direct payments) and fiscal (e.g. reduced taxes) instruments aiming at early adopters or the stabilization of given demand; common examples are feed-in-tariffs, rebates, preferential loans, or tax incentives
D3	Pricing emissions exter-nalities	Policies should correct market prices for existing technologies (e.g., coal based power production) which do not reflect full social costs.	"Any policy to address global warming must address this failure of prices to accurately reflect social costs, for example, through a tax on carbon or a 'cap and trade' system of emissions targets." (p. 1013)	Existence of mechanisms that modify market prices of fossil fuels and other conventional technologies to reflect negative externalities; e.g., taxes on competing technologies, carbon taxes, emission trading schemes
D4	Govern-ment procure-ment	The diffusion of alternative energy technologies can be spurred by government procurement policies.	"Government will be an important user of some of the new energy technologies, and public procurement policies can be used to promote certain technologies or applications … governments might be better advised to use procurement competitions to encourage the development of climate-friendly energy technologies that could be implemented in public applications." (pp. 1020, 1021)	Existence of public procurement or investment programs aiming at public users buying alternative energy technologies, or energy

Code	Policy design principle	Description and rationale	Exemplary statements from MNM	Qualitative indicators (proxies)
D5	Public diss-emination programs	Public information and dissemination programs to facilitate networking amongst various actors, such as (prospective) users and producers in order to spur adoption.	“These closely linked processes of adoption and technological improvement may benefit from public information dissemination programs that link early adopters with one another and with major producers and R&D organizations.” (p. 1013)	Existence of dissemination mechanisms that link existent (and prospective) users with each other to share in-use experiences; this covers, e.g., education and training of (potential) adopters, public events, websites and related mechanisms
C	**CONDITIONS: Conditions or characteristics to either supply or demand policies**			
C1	Long-term support	A long-term perspective and stable and credible policy commitments are necessary for developing and improving alternative technologies and their adoption.	“… public programs should focus on long-term support for the development and improvement of relevant technologies, rather than seeking a one-time technological breakthrough … Stability and credibility are therefore important goals for the design of energy R&D programs, as well as for the demand-side policies …” (pp. 1020, 1022)	The basic policy principle (e.g. research funding, feed-in system, government procurement, tax incentives) was at least five years in effect (without threat to be discontinued in between) and received relatively continuous funding during that timeframe
C2a	Decen-tralized programs	Decentralization of policy programs spans diverse instances responsible for technology priority-setting, funding, and performance control.	“A considerable amount of decentralization is desirable or even essential in an energy R&D program that spans such a diverse array of technologies, industries, countries, users, and applications, and which involves such a wide range of activities.” (p. 1021)	Existence of more than one instance that prioritizes, funds, and controls for technology performance; e.g. different government agencies in charge of policy definition or execution
C2b	Centralized leadership	A centralized administrative structure sets overall priorities, monitors progress and evaluates performance.	“… a centralized administrative structure for setting broad priorities, monitoring overall progress, and evaluating performance is a necessary complement to a decentralized program structure.” (p. 1021)	Existence of one central authority (regardless on which level, local, state, or national) that defines overall policy goals, monitors, and evaluates goal achievement; e.g. a single federal agency that is responsible for the policy strategy definition and execution
C3	Technologic al diversity	The energy-related technologies that are involved in any solution to global warming are extraordinarily diverse and will be developed and produced by firms in many different industrial sectors.	“An effective R&D program to combat climate change must support the development and deployment of many different technologies that will be employed in a diverse array of sectors …” (p. 1019)	Coverage of additional renewable energy technologies besides solar
C4	Global cooperation	Alternative energy technologies address a global problem but are applied locally; co-operation of national governments and even international subsidies are necessary to work on this global-local challenge.	“… it is critically important to work out an appropriate division of labor among national governments and to create effective mechanisms for cooperation and coordination. Much more than ‘technology transfer’ will be required, although support for the global dissemination of information and, potentially, subsidies for other nations …” (p. 1022)	1.) National actors that co-operate across borders *or* 2.) Definition of goals that affect more than one country *or* 3.) Transfers of money, knowledge, work force etc. between countries

Table A. 1: Coding push vs. pull policy proscriptions of Mowery, Nelson and Martin (2010)

PV-related policies in the U.S.			Technology push								Demand pull					Conditions					Solar Value Chain					
Policy	**Year**	**Policy Instrument**	**T1a**	**T1b**	**T1c**	**T1d**	**T2**	**T3**	**T4**	**T5**	**D1**	**D2**	**D3**	**D4**	**D5**	**C1**	**C2a**	**C2b**	**C3**	**C4**	**Basic**	**R&D**	**Manufact.**	**Demo.**	**Interface**	**Deploy**	**Use**
Solar Photovoltaic Energy Research, Development and Demonstration Act	(1974-1978) 1978-2009	R&D funding	+	+					+							+		+		+	+	+		+		+	
Public Utility Regulatory Policies Act (PURPA)	1978-present	Regulatory instrument (mandate)														+		+	+						+		
Energy Tax Act of 1978 (including Tax Reform Act of 1986)	**1978-1992**	**Package**																									
Residential Energy Tax Credit	1978-1985	Incentives (tax credit)										+						+	+							+	
Business Energy Tax Credits	1978-1992	Incentives (tax credit)										+						+	+							+	
(Modified) Accelerated Cost Recovery System (MACRS)	1981-1986 1986-present	Incentives (tax credit)										+				+		+	+							+	
Renewable Portfolio Standard (RPS)	1983-present	Regulatory instrument (mandate)									+					+	+		+							+[1]	
Energy Policy Act (EPAct) 1992, EPAct 2005	**1992-present 2005-present**	**Package**																									
Federal Business Investment Tax Credit (ITC)	1992-2005 2005-2016	Incentives (tax credit)										+				+		+	+							+	
Production Tax Credit (PTC)	1992-2003 (no solar) 2004-2005 (w/solar) 2005-present (no solar)	Incentives (tax credit)										+						+	+							+[1]	
Renewable Energy Production Incentive (REPI)	1992-2005 2005-2026	Incentives (tax credit)										+						+	+							+[1]	
Tribal Energy Program	1994-present	Education/outreach, incentives (grants), financial (funds to sub-national governments)							(+)			+			+	+	+	+	+					+	+	+	
Photovoltaic Energy Commercialization Program	2005-present	Government procurement								(+)		+		+			+	+								+	
Loan Guarantee Program (for Innovative Energy Technologies)	2007-present	Incentives (preferential loans)										+						+	+				+	+		+	
Residential Renewable Energy Tax Credit	2006-2016	Incentives (tax credit)										+						+	+							+	
(New) Clean Renewable Energy Bonds (CREB)	2005-present 2009-2010 (New)	Incentives (preferential loan)										+						+	+							+	
Federal Utility Partnership Working Group (FUPWG)	1994-present	Education/outreach													+	+		+	+				+	+			
State Energy Program	1996-present	Incentives (tax credit, preferential loans), education/outreach										+			+	+	+	+	+						+	+	
E.O. 13123 ("Greening the Government Through Efficient Energy Management")	1999-2007	Policy process (institutionalization), government procurement												+		+	+	+	+							+	+

PV-related policies in the U.S.			Technology push								Demand pull					Conditions						Solar Value Chain						
Policy	**Year**	**Policy Instrument**	**T1a**	**T1b**	**T1c**	**T1d**	**T2**	**T3**	**T4**	**T5**	**D1**	**D2**	**D3**	**D4**	**D5**	**C1**	**C2a**	**C2b**	**C3**	**C4**	**Basic**	**R&D**	**Manufact.**	**Demo.**	**Interface**	**Deploy**	**Use**
Greening of the National Park Service	1999-present	Education/outreach, government procurement												+	+			+	+							+	
Energy Efficiency and Renewable Energy (EERE) International Activities	1999-present	Education/outreach, R&D funding	+	+	+										+	+		+	+	+		+			+		
Green Power Partnership	2001-present	Voluntary agreement, education/outreach												(+)	+	+		+	+								+
Solar Decathlon	2002-present	Education/outreach, demonstration projects,						(+)	+						+	+		+						+	+	(+)	
Rural Energy for America Program (REAP) Grants	2002-2008 2008-present	Incentives (grants; preferential loans)										+				+	+	+	+							+	
Interconnection Standards for Small Generators	2005-present	Regulatory instrument														+		+	+						+		
State and Local Climate and Energy Program	**2005-present**	**Package**																									
State Climate and Energy Program	2005-present	Education/outreach, policy process													+	+	+	+	+						+	+	+
State Climate and Energy Partner Network (previously: EPA's Clean Energy–Environment State Partnership)	(2005-2009) 2009-present	Education/outreach, policy process													+		+	+	+						+	+	+
State Utility Commission Assistance	2005-present	Education/outreach													+		+	+	+						+	+	+
Climate Showcase Communities Grant	2009-present	Education/outreach							+						+		+	+	+					+		+	
Solar America Initiative (SAI)	**2006-2009**	**Package**																									
Solar America Board for Codes and Standards	2007-2009	Education/outreach, regulatory instrument (codes/standards)													+			+							+		
Solar America Cities	2007-2009	Financial (funds to sub-national governments), education/outreach										+		+	+		+	+							+	+	
Solar America Showcases	2007-2009	Education/outreach													+			+								+	
Solar America Future Generation PV	2007-2009	R&D funding	+	+		+												+			+	+					
Solar America PV Incubator	2007-2009	R&D funding	+	+		+			+									+				+		+			
Solar America Technology Pathway Partnerships	2007-2009	R&D funding	+	+	+				+									+				+	+	+			
Solar America University PV Product and Process Development	2007-2009	R&D funding	+	+	+													+				+					
Technology Commercialization Fund (TCF)	2007-2008	Incentives (grants), demonstration projects			+				+			+					+	+	+			+		+			
Energy Independency & Security Act (EISA) of 2007	**2007-present**	**Package**																									
Solar Energy Research and Advancement Act	2007-present	R&D funding	+	+	+				+								+	+				+		+	+	(+)	
Energy Efficiency and Conservation Block Grants	2007-present	Incentives (subsidies)										+		+			+	+	+						+	+	

PV-related policies in the U.S.			Technology push								Demand pull					Conditions					Solar Value Chain						
Policy	**Year**	**Policy Instrument**	**T1a**	**T1b**	**T1c**	**T1d**	**T2**	**T3**	**T4**	**T5**	**D1**	**D2**	**D3**	**D4**	**D5**	**C1**	**C2a**	**C2b**	**C3**	**C4**	**Basic**	**R&D**	**Manufact.**	**Demo.**	**Interface**	**Deploy**	**Use**
Renewable Energy Innovation Manufacturing Partnership Program	2007-present	R&D funding	+	+					+							+		+	+			+	+	+			
Green Jobs Act (based on Workforce Investment Act (WIA) of 1998)	2009-present	Education/outreach															+	+	+				+		+		
International Energy Programs	2007-present	Education/outreach													+					+						+	
E.O. 13432 ("Strengthening Federal Environmental, Energy, and Transportation Management")	2007-present	Policy process (institutionalization), government procurement												+		+	+	+	+								+
Advanced Research Projects Agency—Energy (ARPA-E)	2007-present	Research program	+	+	+	+												+	+		+	+					
National Defense Authorization Act	2008-2009	Government procurement, education/outreach	+	+										+				+	+							+	
Western Renewable Energy Zones (WREZ) Project	2008-present	Policy process															+	+	+						+		
Energy Improvement and Extension Act 2008	2008-present	Incentives (tax, tax credit)										+	+					+	+							+	
E.O. 13514 ("Federal leadership in Environmental, Energy, and Economic Performance")	2009-present	Policy process (institutionalization), government procurement												+		(+)	+	+	+							+	+
American Recovery and Reinvestment Act (ARRA)	**2009**	**Package**																									
Renewable Energy Grants Program	2009-2011	Incentives (grants)										+						+	+							+	
Energy Frontier Research Centers (EFRCs)	2009-2013	Research program	+	+		+												+	+		+						
Advanced Energy Credit for Manufacturers	2009-present	Incentives (tax credits)																+	+				+				

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Table A. : PV-related policies in the United States, 1974-2009

PV-related policies in Germany			Technology push								Demand pull					Conditions					Solar Value Chain						
Policy	**Year**	**Policy Instrument**	**T1a**	**T1b**	**T1c**	**T1d**	**T2**	**T3**	**T4**	**T5**	**D1**	**D2**	**D3**	**D4**	**D5**	**C1**	**C2a**	**C2b**	**C3**	**C4**	**Basic**	**R&D**	**Manufact.**	**Demo.**	**Interface**	**Deploy**	**Use**
1,000 Roofs Solar Power Program	1990-1995	Incentives (grants), Education/outreach (information dissemination), R&D funding	+							+		+			+		+	+				+		+		+	
KfW Environment and Energy Saving Program (ERP)	1990-2008	Incentives (preferential loans)										+				+		+	+							+	
Electricity Feed-In Law (StromEinspG)	1991-2000	Incentives (feed-in tariffs), regulatory instrument									+	+				+		+	+							+[1]	
Full Cost Rates	1993-2000	Incentives (feed-in tariff)									+	+				+	+									+[1]	
100 Million Program	1995-1998	Education/outreach (promotion), incentives (grants)										+						+	+							+	
Ordinance on the Fee Schedule for Architects and Engineers	1995-present	Regulatory instrument (codes/standards)									+	+				+		+	+						+		
Green Power	1996-present	Incentives (feed-in tariff) (government procurement)										+		(+)		+	+		+							+[1]	(+)
Federal Building Codes for Renewable Energy Production	1997-present	Regulatory instrument (codes/standards)									+					+		+	+						+		
Energy Industry Act	1998-present	Regulatory instrument									+					+		+	+						+		
100,000 Roofs Solar Power Program	1999-2003	Incentives (preferential loans)										+						+								+	
Renewable Energy Sources Act (EEG)	2000-present	Incentives (feed-in tariffs), regulatory instrument									+	+				+		+	+							+[1]	+
KfW Program Producing Solar Power	2005-2008	Incentives (preferential loans)										+						+								+	
5th Energy Research Program	2005-2010	R&D funding, research program	+	+	+		+		+	+						(+)	+		+		+	+		+			
Photovoltaic Technology Evaluation Center (PV-Tec) at Fraunhofer ISE	2006-present	R&D funding, voluntary agreement	+	+	+		+		+	+						+	+	+			+	+		+			
Climate Protection Investment from Sale of Carbon Allowances	2008-present	Incentives (grants)										+			(+)	+		+	+							+	
KfW Renewable Energies Program	2009-present	Incentives (preferential loans)										+				+		+	+							+	
6th Energy Research Program	2011-present	R&D funding, research program	+	+	+		+		+	+						(+)	+		+		+	+		+			

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Table A. : PV-related policies in Germany,1990-2011

PV-related policies in China			Technology push								Demand pull					Conditions					Solar Value Chain						
Policy	**Year**	**Policy Instrument**	**T1a**	**T1b**	**T1c**	**T1d**	**T2**	**T3**	**T4**	**T5**	**D1**	**D2**	**D3**	**D4**	**D5**	**C1**	**C2a**	**C2b**	**C3**	**C4**	**Basic**	**R&D**	**Manufact.**	**Demo.**	**Interface**	**Deploy**	**Use**
Brightness Program	1996-present	Policy process (strategic planning)									+				+	+	+	+								+	+
Preferential Tax Policies for Renewable Energy	2003-present	Incentives (taxes, tax incentives)										+							+	+			+			+	
Renewable Energy Development Targets	2006	Policy process (strategic planning)									+							+	+							+	
Renewable Energy Law	2006-2009	Policy process (strategic planning)	+	+			+				+	+				+	+	+	+			+			+	+	+
Medium and Long Term Development Plan for Renewable Energy	2007-present	Policy process (strategic planning)	+	+							+	+				+	+	+						+	+	+	
National Climate Change Program	2007-present	Policy process (strategic planning)	+	+			+				+		+			+		+	+	+	+	+	+		+	+	+
International Science and Technology Cooperation Programme for New and Renewable Energy	2008-present	Education/outreach (information dissemination), R&D funding	+	+				+											+	+	+	+					
Renewable Energy Law amendments	2009-present	Policy process (institutionalization), public investment (infrastructure), R&D funding	+	+			+				+	+	+			+	+	+	+			+			+	+	+
Golden Sun Programme	2009-present	Incentives (grants)										+			+		+	+							+	+	
Renewable Electricity Premium (surcharge)	2009-present	Incentives (feed-in tariffs)										+					+	+	+							+	
Building Integrated Solar PV Programme	2010-present	Incentives (grants)										+					+									+	
Interim Feed-in Tariff for Four Ningxia Solar Projects	2010-present	Incentives (feed-in tariffs)										+			+		+									+	
Solar PV feed-in tariff	2011-present	Incentives (feed-in tariffs)										+					+	+								+	

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Table A. : PV-related policies in China,1996-2011