Mental Models in an Emerging Industry: The Photovoltaic Industry in Massachusetts

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Abstract

A model-based field study was conducted to elucidate the detailed beliefs of participants in the photovoltaic industry. The mental models of system participants are important because participants are the people with the greatest knowledge about the system, because in any policy solution they are the critical actors, and because it is their decisions and actions from which the behavior of the system emerges. Seventeen experts were interviewed. The knowledge they conveyed was expressed as a set system dynamics models; these models were characterized and compared. The informants all expressed dynamic growth as a result of reinforcing feedback processes, but few perceived of any balancing feedback. Characteristics of the system they perceive include loosely coupled segments resulting in weak feedbacks. Their beliefs indicate successful policies will have to recognize the difference between global and local supplies, and large and small customers.

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Introduction

The world economy is currently based on the consumption of energy stored long ago as fossil fuels. The amount of energy thus stored is finite, and the current rate of consumption produces waste above the absorption capacity of the ecosystem. Eventually, people will have to balance their energy consumption with the Earth's energy input, and their waste production with the capacity of the ecosystem to absorb and purify it. Renewable energy refers to modes of energy production—such as solar, wind, and biomass—that meet these requirements. As a relatively new set of technologies, renewable energy has to compete with the established energy infrastructure. Prices are high and barriers to commercialization persist. Some of the value and cost to society embodied in the energy system is beyond the market, reflecting externalities and public goods problems. Recognizing this, governments have established policies to promote renewable energy. Yet more than 30 years after the oil crisis first motivated an interest in alternative energy sources, renewables are still a tiny fraction of energy production in the United States.

It is not surprising that change is slow. Major changes in the energy infrastructure are associated with economy-wide shocks (Schumpeter, 1962). A number of forces lead to barriers to change, including cost advantage to the existing technology (Arthur, 1989), power wielded by existing interests (Emerson, 1962), institutionalized practice (DiMaggio & Powell, 1983), and the interplay of social and economic forces (Greenwood & Hinnings, 1996). It is extremely difficult to coordinate action to bring about such a major change, both because agency is diffused among many actors and because actors are embedded within dependencies and constraints (Garud & Karnøe, 2003). Yet new technologies do occasionally overcome the institutionalized advantages of old (Oliver, 1992). The question is how this can be purposefully brought about, before environmental limits force drastic action.

Enacting major change will require some mix of technological development (OECD & IEA, 2003), strategic action (Oliver, 1991), entrepreneurship (Garud & Karnøe, 2001), market creation (Stoneman & Diederen, 1994) and public policy (Norberg-Bohm, 2000). Each of these affects and is in turn affected by the others (Carlsson & Stankiewicz, 1991; Grubb *et al.*, 2002); in particular we choose policy in the hope of bringing about desired change by encouraging the other activities. The effects of intervention are complex, and they occur within a complex system (Levy & Rothenberg, 2002) characterized by heterogeneous actors and multiple forces. Intervening in a complex system is unlikely to be successful without a thorough understanding of the system (Sterman, 1994).

We do not understand enough of the energy system to make informed policy choices, but we cannot safely delay taking action. While we continue to act based upon our limited understanding of how renewable energy technology can best be diffused, we should strive for better understanding, and improve our policy as we learn. This leads to the question this research is designed to address: How does the renewable energy industry work as a system, and how could that system work better?

In the renewable energy industry, actors of various kinds—manufacturers, developers, researchers, customers, regulators, advocates, and competitors—interact in both market and non-market transactions. As material flows through the value chain, actors exchange information, both explicitly and indirectly. There are many variables, some not easily measured, and many paths for feedback. For example: research, experience, and economies of scale all lead to lowered cost; producers communicate cost via their prices, directly to customers but also indirectly as an input to market price. Buyers act on this information when they make orders or purchases, which trigger material flows but are also signals of demand. Sales generate the resources used to invest in research or a larger factory. The pattern of past sales affects confidence, which affects the cost of financing, which affects the cost to the manufacturer, and so on.

Each decision maker has some understanding of this complex system. Their understanding is probably most accurate in the immediate area of their business, becoming more approximate further out. As decisions are based upon mental models, divergent mental models may lead to counterproductive actions (Fligstein, 1996). Differences might be particularly harmful to an emerging field (Maguire *et al.*, 2004). Industry creation requires mobilization and common action, industry interest balanced with firm interest (Aldrich & Fiol, 1994; Best, 2001). Working towards a common goal, whether coordinated or merely through common interest, results from shared beliefs (Berger & Luckman, 1967). The degree to which mental models are shared, and building towards a degree of shared understanding if it is missing, are as important as the content of participants mental models.

Effective policy design will require an understanding of system structure, and participants' mental models represent both information about and components of the system. Effective policy implementation will require the active participation of participants. To achieve cooperation, policy will have to be designed taking into account the nature of the actors as well as the nature of the system, and be implemented based on a shared understanding of how the system works, what is to be done, and why. The purpose of this paper is to elucidate the detailed beliefs of experts in support of models of the renewable energy industry. To do so I attempt to answer the following research questions: *What are the mental models of participants in the renewable energy industry? How widely are mental models shared among participants?*

Methods

The full study is designed to gather the mental models of participants in the photovoltaic industry, and express those mental models in a formal language so that they can be compared, analyzed, tested, and simulated. A model-based field study (Forrester, 1994; Lane, 1994) adds formal modeling language to the techniques of exploratory qualitative research, making it possible to draw conclusions about system behavior from knowledge of system structure. While this is applied rather than theoretical research, it falls within the realm of what Karl Weick (1995) includes in theorizing: interpretation of a particular case. Therefore. techniques suitable for the discovery of theory (e.g. Glaser & Strauss, 1967) were applied, while the exploration remained grounded in existing theory. Inductive, exploratory, qualitative research methods aimed at theory (Creswell, 1994; Strauss & Corbin, 1994) are very much like the techniques of system dynamics consulting practice at the science-action interface (Morecroft & Sterman, 1994; Scholl, 2004; Sterman, 1994). These are pragmatic approaches that work towards useful and credible explanations rather than “truth” (Locke, 2001; Sterman, 2002).

In brief, participants in the photovoltaic industry were interviewed to discover their mental models; mental models were expressed as system dynamics models; these were characterized, compared, and combined to learn how the renewable energy industry works as a system. Participants’ everyday language was used when building models. This was discovered during the course of the interviews, and influenced the conduct of later interviews. In fact, using an inductive approach means that stages of my research overlapped and did not proceed consecutively, but may be described as: entry, sampling, data collection, data analysis, model testing, and exit.

Informants were recruited based on their interest in learning about the industry, improving its performance, or promoting renewable energy. Seventeen informants were interviewed, drawn from a deliberate or theoretical sample (Locke, 2001; Strauss & Corbin, 1994). Procedures for the protection of human subjects were approved by the author's university Institutional Review Board. During the interviews, informants were asked for advice on further informants. As the study progressed, the names provided are beginning to repeat or include those already interviewed, giving evidence that adequate coverage is being achieved.

Each informant participated in a semi-structured, open-ended interview patterned on methods for elucidating cognitive maps (Axelrod, 1976; Roberts, 1976; Wrightson, 1976), causal maps (Langfield-Smith & Wirth, 1992; Markóczy & Goldberg, 1995), and system dynamics models (Forrester, 1994; Luna-Reyes & Andersen, 2003). Interviews lasted between 1 and 2 hours, and usually occurred at the informant's place of work. All interviews were recorded with the informants' consent. Additionally, notes were taken in the form of lists and sketches on 18x24 inch newsprint. The large format sketches provided a visual aid for the joint production of knowledge: they were referred to and modified throughout the interviews; the informants occasionally drew them directly; they provided an instant feedback that ensured mutual understanding. The sketches acted as both data and early stage analysis (Luna-Reyes & Andersen, 2003).

Analysis began during the interview, although collecting mental models was the focus. Dedicated analysis is occurring between and after interviews, concurrently and constantly as the research progresses (Locke, 2001). This is an inductive approach to system dynamics (Burchill, 1993), consisting of iteratively defining variables, grouping them into causal statements, and keeping a record of inferences. To characterize the beliefs of informants, system dynamics models were developed expressing the content of each interview. Burchill (1993) and Axelrod (1976) each provide evidence that developing causal diagrams from text is reliable. The models developed were sorted into themes, processes, and structures that represent the various beliefs of the informants. A description of these modeled beliefs and their distribution follows.

Beliefs of the Participants

The data collected must be understood as a joint product of researcher and informant (Alvesson, 2003; Fontana & Frey, 2000) rather than a pure collection of existing mental models. In addition, only fraction of each participants full range of beliefs could be expressed in any interview. The data collection was centered on the participant's view of the most important aspects of his or her particular business or area of activity. The PV market has many segments and the informants occupied several stages along the value chain. For all these reasons, it is to be expected that the mental models expressed during the interviews will vary even when covering the same process. This need not necessarily indicate that one view is less accurate or less sophisticated than the other, although that might be the case.

All of the informants agreed on at least one point: the photovoltaic industry is a dynamically growing system. There may be constraints, but all see either the actual or the natural reference mode as exponential growth for the foreseeable future. Their views of system structure in general support their perceived reference mode. All expressed at least one positive feedback process explicitly. There are several interesting features of their mental models, as described in detail below:

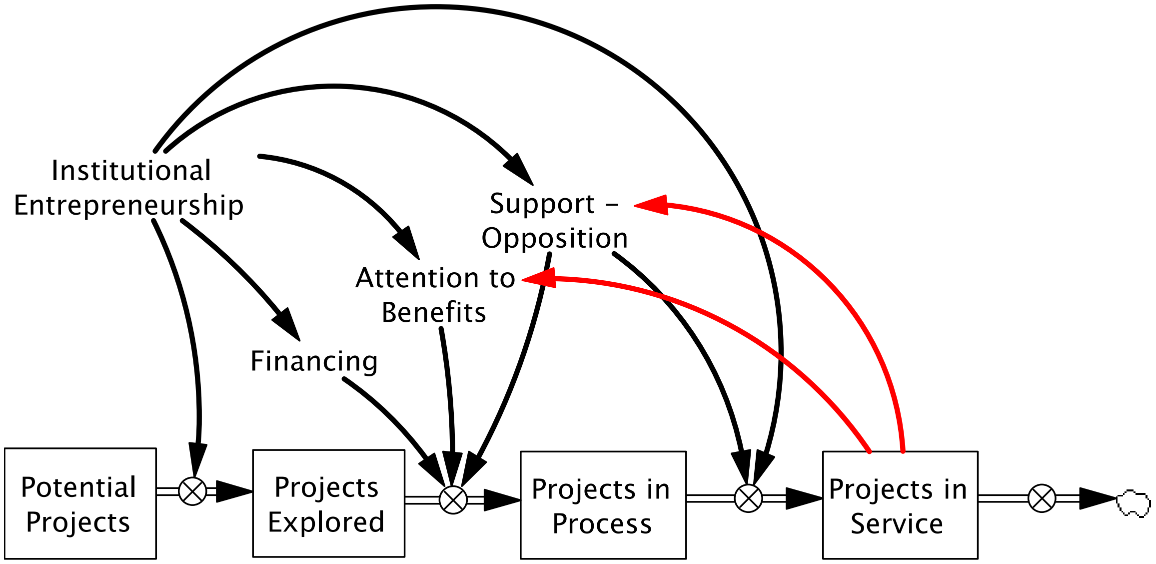
- The PV industry is two difficult markets served by a supply chain of limited capacity
- Informants hold three different dynamic hypotheses about what causes market growth
- There are a couple of hypotheses about lesser dynamics or details
- There are five versions of a stock-and-flow structure in informants' mental models
- Informants perceived a range of positive feedback processes
- Only a few perceived any negative or balancing feedback
- Institutionalization is an important part of the renewable energy industry
- Informants have their own beliefs, and beliefs about the institutionalized beliefs of others

Markets and Supply

The informants occupy several different segments of the PV industry: manufacturing, installation, government, and advocacy. They also enacted several different roles, I describe as: 'getting projects done'; 'growing the market'; 'making sales'; and 'developing policy'. From their different perspectives, they see different market and supply segments, and also described the separation of those segments: two separate and difficult markets—commercial and residential—and a limited supply chain with local and global components.

The commercial and government market is organized around the project. These are tens to hundreds of kilowatts, on government or educational, institutional or business buildings. The market for these projects is difficult because it takes constant intervention to push projects through a complex process (see figure 1). Interested parties in various positions search out potential projects, try to arrange financing, try to convince others to support the project. The people who do this can be classed as institutional entrepreneurs (DiMaggio, 1988; Fligstein, 1997): they are trying to found, challenge, or change institutions. In particular, an important part of ‘getting projects done’ is trying to convert their own or a target organization to new practices or new ways of assigning value.

Figure 1: Commercial market structure

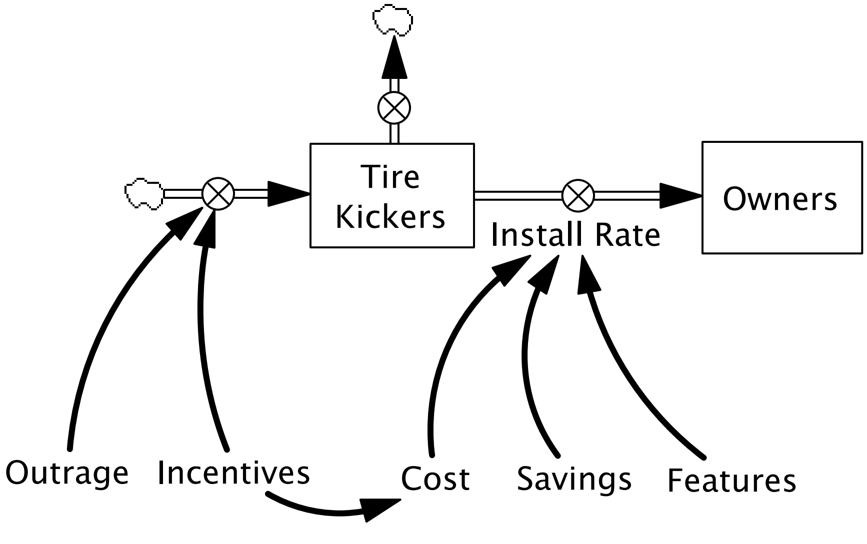


Often, there is a strong separation of budget and authority between capital funds, which have to pay for PV, and operating funds, which reap the benefit. Because of the disconnect, PV and other energy saving measures meet resistance from facilities managers and budget managers, even with high net present value. Obtaining grants and other sources of funding, overcoming resistance, and maintaining enthusiasm for a project through to completion takes a high level of institutional entrepreneurship. Informants hoped that projects might someday become routine, but whatever feedback there is to learning or legitimacy is slow enough that no informants had perceived it yet.

The residential market is lead by homeowners. Typically, a homeowner will call for their own motivation: outrage over global warming or heating bills or the price of gas; interested in cutting electric bills; or attracted by the prospect of a grant. Many of these motivators have little to do with PV; consumers are unfamiliar with the costs and benefits, and energy issues in general. A residential system costs around 20 thousand dollars, one can expect to get 8 to 12 thousand of that back in grants, and then the system will offset some fraction of a 50 or 100 dollar monthly electric bill. Calculated payback period can be 5-15 years, but PV is not perceived as adding to the resale value of a home.

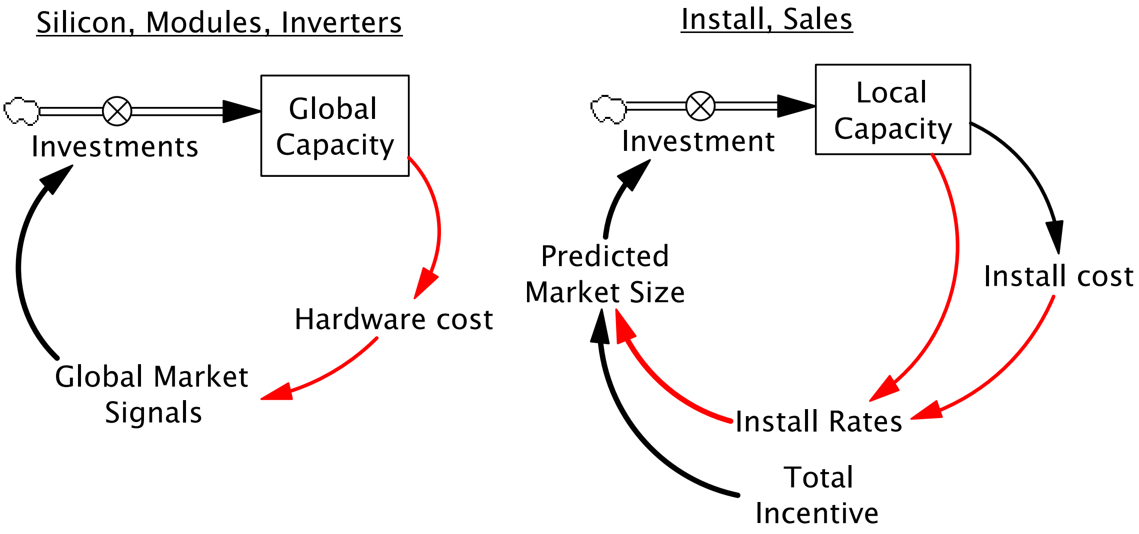
The residential market is difficult because this results in more looking than buying (see figure 2). Retailers cite rates of one sale per ten calls or worse. Those that do buy value other features like greenhouse gas reductions, independence from big business, or environmental chic. It is difficult for installers to make profit, and they are not motivated to invest in marketing since this only increases 'tire-kicking'.

Figure 2: Residential market structure



The supply chain is difficult because there are limited signals and therefore weak feedback loops. All sales are local, but a lot of the supply chain is global; the separate dynamics are shown in figure 3. Most of the 'hardware', from silicon feedstock through completed PV modules, along with inverters and even racking systems, respond to global dynamics. The limiting factor for the past few years has been silicon feedstock, since PV cells passed microchips as the largest user of silicon. The segmentation of local markets makes it difficult for hardware manufacturers to make predictions of global market size. High component prices certainly attract capacity investments in that segment; but lower overall hardware costs can attract investments to the extent they lead to a rise in sales. Over half of global PV sales are in Germany, so market conditions there (under high feed-in tariffs for renewable energy) dominate hardware costs everywhere.

Figure 3: Supply chain structures



Local costs however vary widely, and follow local market conditions. Since incentives are so important, local markets are defined by common policy, which means each US state, or each EU country. Installation, distribution, and marketing are all local; this is the cost of labor, the cost of making a sale, and markup. Investments in local capacity drive local costs, and are attracted by predictions of market size. There is a weak feedback from past growth, but the main indicator used by distributors and installers is total expenditures on incentives. PV companies chase local subsidies, concentrating on the perceived hot market. Germany attracted 60% of the global PV market because of large expenditures for feed-in tariffs, California 70% of the US market with tax credits. In both these cases, declining installation and marketing costs followed. What is pointed to as a local success story is Japan, which had high but declining subsidies to start this feedback loop, and now has 20 % of the world market with no rebates.

Dynamic Hypotheses

Though people commonly look for proximate causes for behavior, deeper understanding looks for the system structure that results in system behavior (Forrester, 2003). No informant would say “my dynamic hypothesis is…”, but from recursive analysis of the data underlying dynamic hypotheses could be identified. Specifically, when informants could identify processes (e.g. learning or scale efficiency) rather than events or actors as causes, these could be combined with expressed causal links to imply the driving structure. Though not every informant expressed any, three such hypotheses for the main reference mode were identified.

The dominant mode that has to be explained is rapid growth in market size from a low base. PV module shipments have been growing by more than 20% per year for over 20 years, if anything accelerating since about 2000. Size and growth rate varies quite a lot by location: large and stable in Japan, large and rapidly growing in Germany, smaller elsewhere but growing fastest where subsidies are high. Another mode is the decline in price, in a decay pattern, with a bump or plateau in the past few years. A third pattern to explain is the widespread belief that, though growing, the PV industry is not growing as fast as it could or should, and particularly in certain locations.

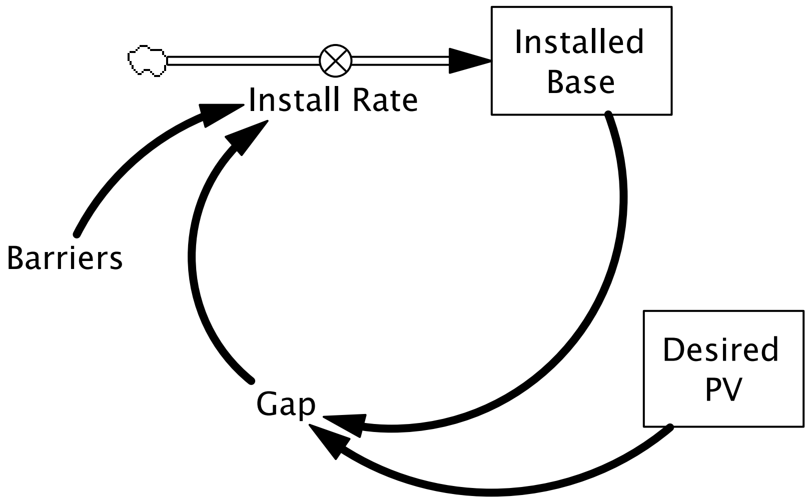
The most common belief was that market dynamics are all about price. Local installed cost per kW after incentives is what leads people to buy. Cost has come down, over decades as PV shipments have gone up. Informants perceive scale and learning curve dynamics and returns from R&D. Thus there would be positive feedback from both current market size (via scale and funds to invest in R&D) and past production and installations (via learning). There is still room to move in several areas: less silicon per cell, better manufacturing techniques, new chemistry, integrated applications: all around making cells cheaper so they are more attractive

Others perceive capacity as having taken over as the most important dynamic. They acknowledge that price has come down and that one of the effects of growing capacity is scale efficiency. But they perceive a sizable market at the present price, and constraints that come from the various capacity issues. Positive feedback increases capacity through reinvestment, which increases market size. Because customers do not seem to make decisions on pure cost, local marketing, distribution, and installation capacity have a greater effect on sales. The principal benefit of incentives is not to lower installed cost, but to attract capacity investments.

Just one informant had a different and sophisticated dynamic hypothesis: that market size is driven by a shortfall in the installed base. There exists a (perhaps implicit) desired level of PV. While various things like price effect how desired PV grows, it is already so much higher than installed base that changes to it are unimportant. Various constraints slowly adjust, increasing the rate at which we close the gap. But the major driver is this large unsatisfied mismatch and the balancing feedback to close it. This dynamic hypothesis is illustrated in figure 4.

Explanations for the secondary reference modes were seen by informants as decidedly more static: much more driven by events than by system structure. For example, the recent plateau in the cost trajectory, and possibly a pause in local market growth, is widely to a one time shock to the silicon supply. Until recently, a main source of silicon for PV was off-spec silicon rejected from the microprocessor industry (Green, 2000). Within the past few years, PV manufacture overtook chipmakers as the largest user of silicon, and the silicon processing sector has not yet caught up to the change.

Figure 4: Installed base gap hypothesis



Another factor perceived as external, especially in light of the silicon shortage, is the adverse effect German policy is having on other locations. German feed-in tariffs are so generous that they reduce the pressure on the supply chain to make progress on cost; Germany attracts so much of the world supply that price and delay are raised everywhere else. Additionally, policy is seen by most informants as given—growth is slower than it might be because support is inadequate, future policy is uncertain, and hidden subsidies for fossil fuels persist. Though there are possible structural explanations for these barriers, by most informants they were seen as exogenous

System Structure and Feedback

Iteratively with uncovering behavior and explanation, analysis of the data uncovered the dynamic structure of the industry as perceived by the informants. What was perceived varied by position in the industry. As is common (Sterman, 1989) the informants had a greater amount of detail over dynamic complexity, for example they would perceive a number of customer types or a number of stages a customer goes through in the decision process, but not a set of feedbacks that made it useful to disaggregate those stocks. The beliefs of informants can be modeled by five versions of a central stock and flow structure, a large catalog of reinforcing feedback loops, and a small number of balancing feedback loops.

Central stock and flow

The many feedback processes in the photovoltaic industry act on and around flows of people, material, and money. This is the main ‘physics’ of the PV market. People explore, adopt, and own PV systems; projects are considered, begun and operated. The number of stages that are perceived along the flow chain, and the number of parallel coflows, is similar to the aggregation assumption of the informants’ mental models. The interviews indicate that they recognize more desegregated flow chains, but that a simplified structure was adequate to model what they described as the important dynamics of the industry.

The detailed supply chain was not considered the most important flow by any informant – each was more concerned with orders or installations or the decisions that led to them. Other important stock and flow structures were commonly perceived, such as capacity or knowledge, but the dynamics always centered on the flow of people, projects, or PV systems. One variable always in or near the central structure is ‘market size’. It is either a measure of or prediction of the installation rate. Informants use several different metrics: a list of projects and sizes, sales in dollars, orders or shipments or installs in megawatts. The Department of Energy tracks shipments in dollars and megawatts (EIA, 2005a), while market research reports (e.g. Makower *et al.*, 2006) predict the size of the industry in billions of dollars. The dimension ‘per year’ is almost always missing, although informants usually did recognize market size as a flow during the interviews.

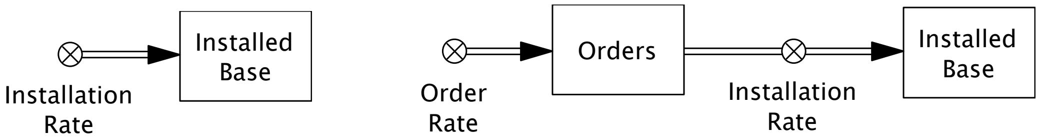
Five categories of stock and flow structure describe informants perception. The distribution of these is shown in table 1, a diagram of each is shown in figure 5. In the first two types, what is most prominent is the flow: the rate of installations and of orders, with the accumulations of those secondary. The priority is reversed in the *Proposed and Completed* type—the stock of projects at each stage is more prominent than the movement between stages. The salience is more mixed in the types that consider adoption. A detailed description of each type follows.

Table 1: Character of informants’ central structure

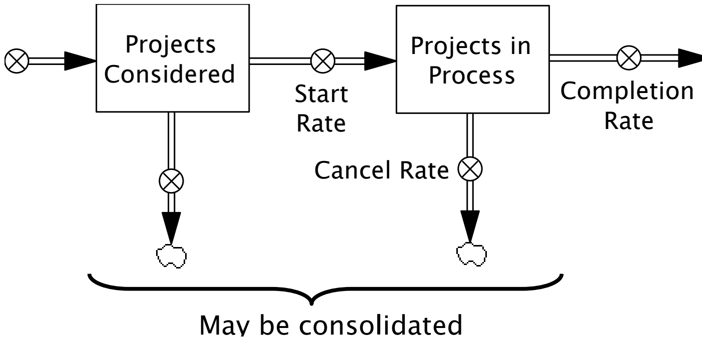
Stocks	Description	Informants
1	Installations	9
2	Orders & Installations	1
2-3	Proposed & Completed	3
2	Explore & Adopt	2
3-4	Explore & Adopt / Installations	2

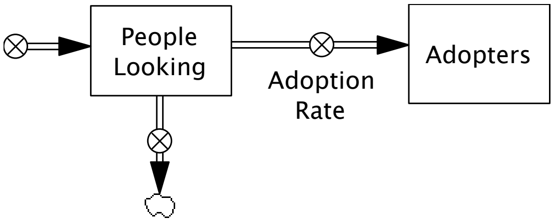
The most common central structure type, called *Installations*, is also the most simple. The important unit is the amount of PV installed and the rate of installation. Installations might be considered in terms of kilowatts, systems, projects, or more than one of these. There is no difference perceived in the dynamics of starting or completing an installation. The factors affecting the decision to buy a PV system are enacted directly in the rate of installation. Installation here is both the verb and the noun—installing some number or amount per year, and the accumulated installed base.

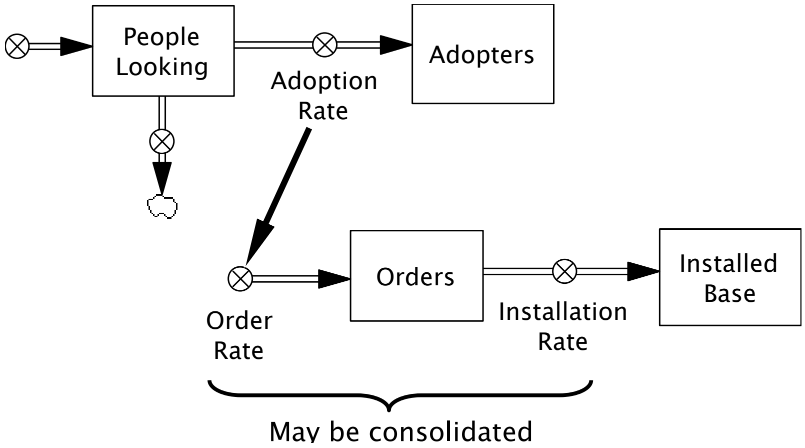
Figure 5: Five versions of central structure


A: Installations

B: Orders & Installations


C: Proposed & Completed


D: Explore & Adopt


E: Explore & Adopt / Installations

Just one informant held an expanded version of this structure, the second type called *Orders and Installations*. Here, the factors affecting sales and those affecting installations are sufficiently distinct so that they are seen as not being consolidated. Separate types of capacity resources are needed to make sales and to complete the install, and they could be divergent. The factors affecting the decision to buy are enacted directly in the rate of sales; following the sale is a more mechanistic process leading to installation. Orders and installs here are principally the flows, in MW per year, although there are important effects of their accumulation.

Three informants had a slightly shifted multi-stage view of material. The *Proposed and Completed* type considers a project well before the ordering stage. Both decisions and physical transformations occur throughout the stages, the decisions tending to be more important. People are part of the project, although the physical aspect of the project is still the unit of analysis. They describe many steps of a project, but have dynamic consequences of one or two phases prior to completion. Note that there is also a shift from stress on flows in *Orders and Installs* to the stocks in *Proposed and Completed*—projects now under consideration rather than the rate of considering new projects.

For four informants, the most important unit was not the amount of PV installed, but the number of people who decide to install it. The *Explore and Adopt* type counts individual people as they move through the stages of a decision. In every case, there is a dynamically important difference between two stages in the decision process, with different factors affecting the decision to start exploration from the decision to finally buy a PV system. Two of these informants considered mainly the people with the effects that depend upon physical installations enacted directly by the rate of adoption. Two other informants (*Explore and Adopt / Installations*) simultaneously accounted for the people deciding and the installation flow, with a clear separation between the decisions and the physical transformations.

To form a consolidated view of the PV industry as a system, we have to consider these different flow structures as representing simultaneous coflows in different market segments. The projects *Proposed and Completed* type best describes the commercial and government sectors, while the *Explore and Adopt* type best matches the residential sector. Completion and adoption sum to form the overall installation rate, the market size, and demands on the supply chain. Feedback loops connect various parts of these chains back to the underlying factors leading to further installations, whether through projects or adoption.

Feedback loops

Describing the industry, informants expressed a variety of feedback processes, far more reinforcing than balancing, along with many processes seen as exogenous. There were two ways informants revealed these beliefs. There could be a shorthand description of a process, for example “returns to scale” or “as PV becomes more familiar…”, particularly for common reinforcing growth processes. Others were uncovered by tracing relationships between variables until the chain either formed a loop or reached an exogenous factor.

In addition to loop polarity, three other ways of categorizing causal loops emerged as useful for describing informant beliefs: origination, mediating variable, and the sense of that variable. Origination refers the loop location on the stock and flow structure. Loops can originate from a measure of the installation rate (*market size* or predicted market size); from the stock of *installed base*; or from some different *accumulation of installations*—a coflow with installation rate but a different time constant than installed base. Two examples are resources, an accumulation of sales, and experience, gained through each installation but not lasting as long as the physical PV panel. The difference in origination is in whether the feedback effect depends on the current pace of the industry, such as for scale efficiency, or on past accomplishments.

Four mediating variables or classes of mediating variables are prominent in informant descriptions as proximate causes of the installation rate and as being involved in feedback loops. These are *price*, to the customer, in dollars per system or per kilowatt; *benefits*, to the customer, in terms of long term savings or performance; *constraints* on the rate of installation; and *psychology*, or cognitive and social aspects perceived by customers. Other mediating variables are important to model, but it is through these four categories that processes have an effect on installations. A majority of processes described by informants can be categorized by origination and mediating variable—table 2 shows a matrix placing the names of feedback loops in the appropriate cells, the few balancing feedbacks shown in red. Table 2 also has a column for exogenous effects by mediating variable, for the factors not (or rarely) connected back to the system.

Finally, the sense of a reinforcing feedback loop is whether it is perceived to be a process of *growing a positive* factor, or *shrinking a barrier*. Reinforcing feedbacks are perceived in two different ways by informants: as a mechanism for growth directly, and as a mechanism for overcoming negative factors. The difference between growing positives and shrinking barriers can be subtle—for example, categorizing their price loops depends on whether the informant believes “cost is a barrier” or “falling cost is a driver”. Table 3 shows the number of informants who expressed each reinforcing process by the sense they perceived it.

Table 2: Loops by origination and mediating variables

	Market Size	Cum. Installs	Installed Base	Exogenous
Price	Scale Proximity Capacity limit	Learning by doing Technology Finance cost		Grants Government R&D
Benefits		Technology	REC price	Production incentives Electricity price Government R&D
Constraint	Capacity invest Capacity limit		Siting	Utility limits Bureaucracy
Psychology	Political power	Education Market maturity Opposition Institutionalization Backlash	Familiarity Experience Goal seeking Perceived need	Outrage Concern Predicted market size

Positive feedback mechanisms for growth are widely perceived generally (Sterman, 2000: section 10.14), while balancing feedbacks much less so (Sterman, 1994). This held for PV industry experts: every informant identified at least one and on average five of the 13 named reinforcing loops, while only six informants described one or two balancing loops. The majority of informants saw no connection between the growth of the industry and barriers it faces. Barriers were almost all static or being overcome by a reinforcing feedback mechanism. For some, the static barriers could be thought of as dynamic only in the limited sense if they think of growing political power enabling changes to restrictive rules.

Table 3: Informants' perception of reinforcing loops

Loop / Process	Growing Positive	Shrinking Barrier
Scale efficiency	5	8
Learning by doing	4	4
Technological improvement	6	2
Finance cost	0	6
Proximity	2	0
Capacity investment	4	4
Familiarity / Reputation	11	5
Experience	1	2
Education	3	2
Market maturity	0	2
Political power	4	2
Overcome opposition	0	4
Institutionalization	2	6

The most common dynamic hypothesis is declining cost. Five reinforcing loops lead to declining price paid by the customer. *Scale efficiencies* are seen to occur at all levels. Manufacturing capacity follows global market size and affects hardware cost; marketing and distribution costs follow local to regional investments; and installation scale efficiencies come mostly from local investments. Very few local markets have the size to affect manufacturing decisions, the exceptions being Germany, Japan, and California. In a special case of scale, with increasing local market size, the density or *proximity* of customers to retailers increases, saving travel time and therefore costs.

The *learning by doing* phenomenon is also seen to be strongest in local costs—marketing and installation have become much cheaper in bigger markets. While learning occurs in manufacturing, other effects are much stronger. In addition to scale, *technological improvement* has a large effect on manufacturing costs. Gains from reinvesting resources into R&D include more efficient manufacturing techniques, using less silicon per module, getting higher output from modules, and developing products that are cheaper to install. One unique cost that was only seen as a barrier to overcome was the *finance cost*. Although the proximate mediating variable is price, finance cost is an institutionalization problem, with borrowing becoming easier as financial institutions become more familiar with renewable energy.

Informants report that customers consider price and benefits separately, including separating the initial cost from the value of electricity generated. The technological improvement loop also affects benefits to the extent that more electricity is generated from the same size system. Government support for R&D affects both price and benefit, but other incentives attach to one or the other: grants are cost, production incentives are benefits. Higher electricity prices also add to the benefit side of PV.

Two informants perceived balancing feedbacks on price and benefits. Renewable energy credits (RECs) provide a means of selling the attributes of renewable energy for both the voluntary market and for compliance with the Commonwealth's Renewable Portfolio Standards (RPS). *REC price* provides a balancing price signal to bring renewable generation up to the RPS mandate, but decreases the rewards to operators thereafter. In responding to supply and demand conditions, price limits growth as market size runs up against *capacity limits*, particularly as happened recently with silicon.

The other common dynamic hypothesis is that capacity growth drives market growth. *Capacity investment* follows market size or predicted market size. The limiting capacity is a constraint in sense that it sets the maximum install rate, but some perceive it in the growing positive sense, as infrastructure to increase sales. Utility resistance and government bureaucracy are exogenous constraints, and balancing feedbacks were perceived via capa*city limits* and using up well supported *siting* for large projects.

Though cost and capacity are the big drivers of informants' dynamic hypotheses, psychological factors had more mechanisms and were more commonly perceived in feedback loops. All but one informant expressed a reinforcing effect from *familiarity or reputation*. For most this is a growing exposure, but some see the familiarity loop as overcoming a current low level of familiarity, or of living down an existing negative reputation left over from earlier, less reliable systems. Where familiarity is a general awareness and favorableness effect, *experience* with installed systems specifically raises the salience of benefits as they become more documented.

Where familiarity and experience occur by the mere existence of installed systems, *education* is an active process mobilizing resources, which can come from revenue. It is interesting that some view customers in the industry as having a high level of interest and positive attitude, with sales only held back by high cost, while others see it as a challenge to overcome negative attitudes. One construct some use to bridge the difference is *market maturity*. An analogy used was that it once took much research to find a personal computer, while now customers can order a customized PC online in minutes. So although customers might be generally familiar with PV, they are far from familiar with the market.

Since so much of renewable energy is related to public policy, *political power* is an important resource. There is a feedback from market size, in particular through number of jobs and job growth. Informants tended to see political power as a cognitive factor, but it could provide a way to connect what they perceived as exogenous government policies. Power at the project level plays out as *overcoming opposition*. Opposition to PV is not as common as the opposition to, for example, siting wind turbines, but it does exist. It is more of a factor if powerful stakeholders have a negative opinion of PV based either on cost or negative reputation, and is expected to fade as successful projects are completed.

A slower process, in effect mostly at the government and commercial level, is the *institutionalization* of renewable energy related practices and the incremental effect on accounting systems, budgeting, and facilities planning, as well as the erosion of practices that prevent taking long term costs into account. Several informants in fact saw renewable energy as an entrée to practices that could institutionalize longer term or sustainability thinking in general, because the price signal for energy is stronger than for other environmental issues.

Psychological factors are part of three balancing feedbacks perceived by one informant each. One held the *goal seeking* dynamic hypothesis, that the dominant force is orders to bring installed PV to an (extremely high) desired level. A more direct political balancing feedback is a form of *backlash* against policies favorable to renewable energy as the industry has success. Finally, because of poor understanding, people underestimate how much PV is required to make a real difference. Because of low *perceived need*, when small gains are made, the urgency to act decreases far more than it should.

Institutional Forces

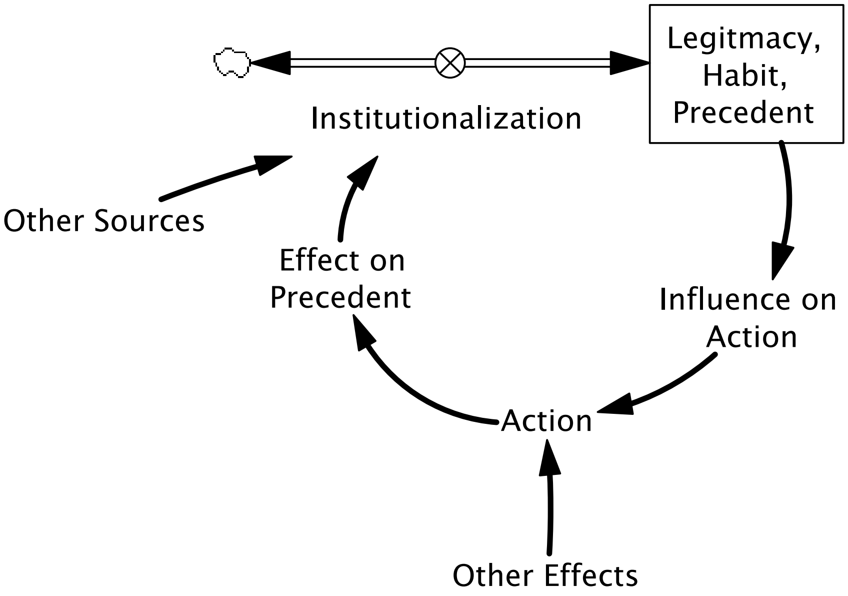
In any institutional field, such as an industry, some beliefs become taken for granted (DiMaggio & Powell, 1983). This is not to label them as inaccurate, although institutionalization can cause practices to persist beyond their utility (Selznick, 1957). In fact, an important part of industry formation is the development of shared beliefs and values (Fligstein, 1996). Several beliefs are widely held across the renewable energy industry (including by this author): exponential growth in all metrics of industry size; that the industry could grow faster but for constraints; a continuing decline in costs; that renewable energy is a net environmental and social benefit.

An institution persistently exerts order effects on action without the need for constant intervention (Clemens & Cook, 1999: 445); institutionalization is developing precedent, habit, legitimacy: the taken for granted assumptions underlying collective behavior. Many informants consciously thought about this cycle as an important feature of the industry.

Institutional entrepreneurship involved in commercial / government projects and in industry building. Those that get projects done are trying to change the way others in their organization think; trying to change what is valued, what is assumed, what is taken for granted. Those attempting to grow the market are trying to achieve these effects on a broader level. They recognize that current practice originated for legitimate reasons, even as they are attempting to change it. Institutionalization is a positive feedback loop or set of parallel loops (Sastry, 2001) that operate via processes like familiarity, legitimacy, habit and precedent (Berger & Luckman, 1967). Every PV system installed or every example of a heterodox decision erodes the legitimacy of existing practice or builds the legitimacy of renewable energy (figure 6).

Informants used different words for it, but understanding life cycle costs, or long term thinking, causes people to recognize the value of renewables. In many current practices, lowest first cost is favored over lowest long term cost. This is not a rational outcome of discount rates, but a consequence of accounting systems, of the separation of capital and operating budgets, of the definition of what bankers lend against. The same or similar sentiments are involved in solving many environmental and sustainability problems. For some entrepreneurial informants, energy is seen as an entrée into more general thinking. It is easier to sell on renewable energy and energy efficiency and then generalize to broader issues, because it is more concrete, easier price signals.

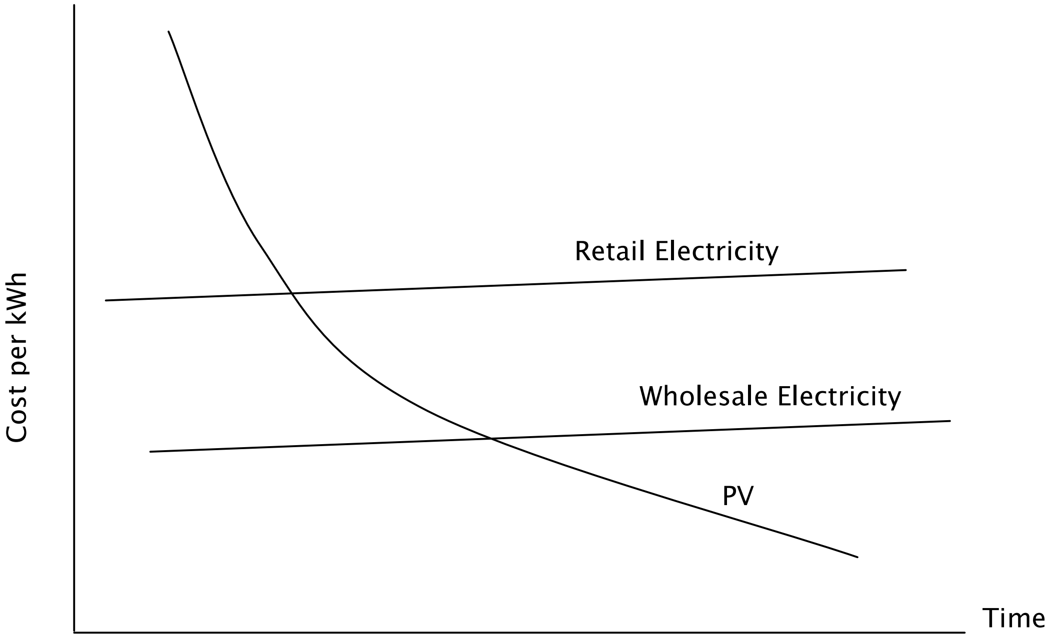
Figure 6: General institutionalization feedback



As examples of persistence of assumptions, of reputation from taken for granted ideas, are these very gendered issues in perceptions of strength and weakness. Coal miners, oil workers, industrial revolution: these are signs of strength. Solar is weak, geeky, Jimmy Carter in a sweater, hippies in the woods. So the intermittency of PV is stressed as a weakness compared to old reliable coal. There seems to be a need to sell PV on strength issues like system reliability and energy independence. These attitudes, assumptions, perceptions of value, these are things renewable energy has to overcome but also things that adopting and exposure to renewable energy can help change. Many informants recognize that this is a campaign for change that will happen over generations.

There are also some predictable misperceptions and biases (Tversky & Kahneman, 1974) widely in evidence. Many actors along the value chain believe that the cost at some other part of the value chain needs to fall before some barrier will be overcome. There exists both misperceptions of the cost trajectory, and recognition that misperception exists. Some believe that there has been or will soon be a sharp drop in costs, rather than the 30 year smooth exponential decline indicated by data. This may be a symptom of the non-linear effect of cost—as costs fall below certain setpoints, new markets open up (figure 7). Those that do recognize the smooth cost decline know that the misperception occurs. This interacts with actors' beliefs about the beliefs of others—some informants think that potential customers are waiting for a sudden drop in price

Figure 7: Cost trajectory compared to market cost.



How Policies Mobilize Dynamics

Intervening to jump start dynamics dominated by positive feedback is a frequent theme in policy and strategy (Argote & Epple, 1990; Arthur, 1989; Grubb *et al.*, 2002). Incentives affect either the cost or benefit of PV, and they attract investment in local capacity. These have to be considered separately, in light of what people will buy and what companies will do to expand. Key to understanding intervention in this context, by the knowledge imparted by these informants, is the separation of local and global market effects, and the different forces in the two difficult market segments.

Photovoltaic modules and their components trade in a global market; learning, scale efficiency, capacity investments and technological change all respond to global conditions. Only the largest policy interventions would be able to affect the cost trajectory of hardware – which has been declining 20% per year for decades in any event (EIA, 2005b). Local costs of installation and marketing however vary widely, and respond to local investments by firms that are seen to chase predicted market size. The largest indicator of future market size is seen to be total local incentives, but the local market can only cover the geography that has the same policy.

In contrast to investors, consumers pay attention to individual subsidies when calculating costs. It does not seem to be a simple net cost of electricity. For the most part, residential consumers must begin exploring PV before costs can be estimated. They begin the process because of outrage, attraction to subsidies, exposure, and so on, not to save on electric bill. The cost net of subsidies of a system if evaluated with respect to various benefits, perhaps including payback time or electricity savings, but only after a considerable education and exploration process. Because outrage is involved, one informant noted that the price of a gallon of gas had a larger effect on PV sales than the price of electricity.

Finally, institutionalization of new practice has to occur, supporting not only PV but sustainable living in general. Adopting renewable energy and energy efficiency measures may have a stronger effect on the conversion to life-cycle thinking than the other way around—saving on facilities operating cost is a concrete example that could lead to the deinstitutionalization of short term, next quarter mindset responsible for unsustainable practices. This is a long campaign. We've been at saving energy for thirty odd years and most people ignore efficiency measures with a six-month payback. It is not a quick feedback in word of mouth, it is a generations-long investment in education, changing attitudes, and challenging assumptions.

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